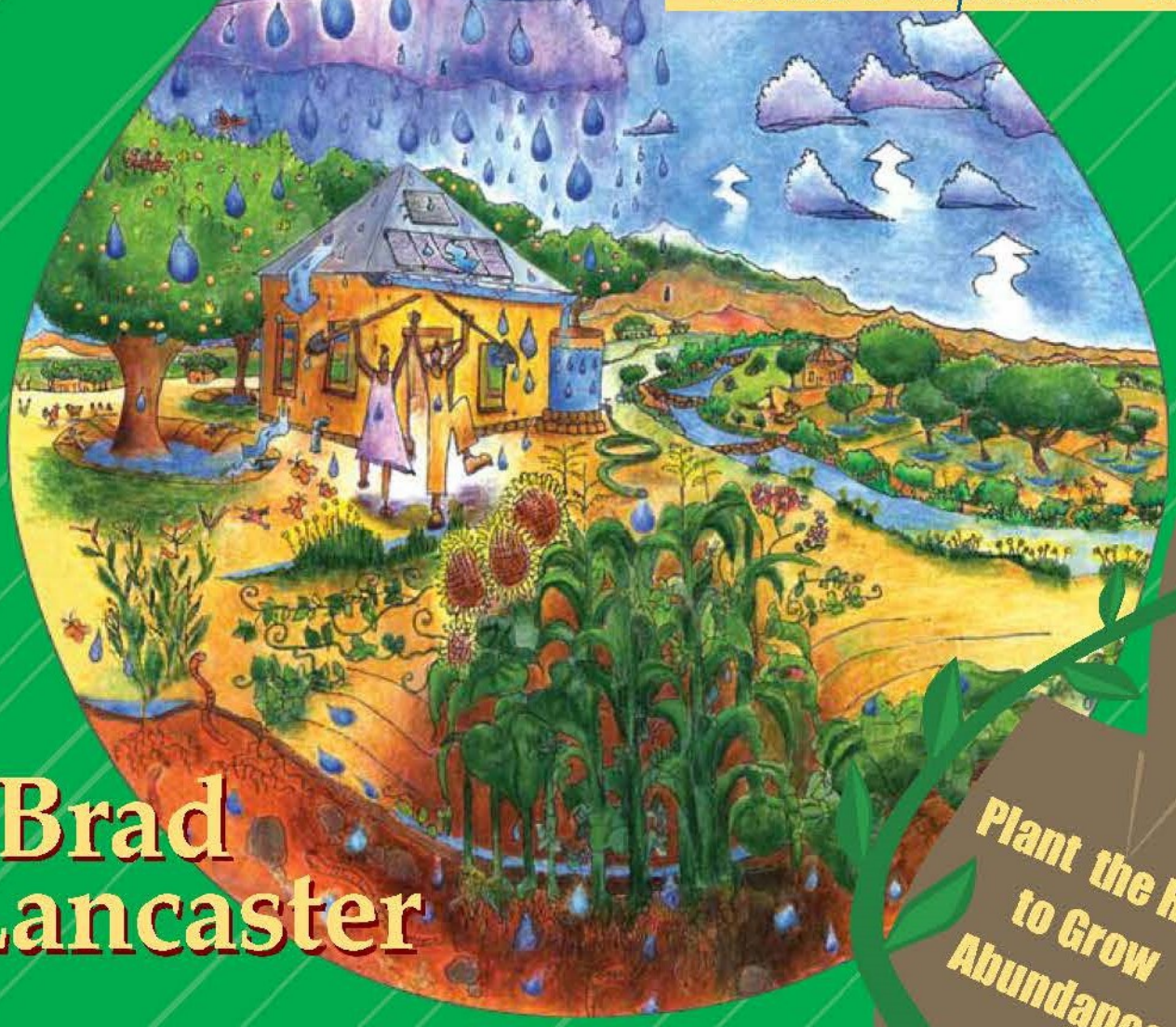
Rainwater Harvesting

for Drylands and Beyond

VOLUME 2 *2nd Edition*
Water-Harvesting Earthworks

revised & expanded—in color



Brad Lancaster

Plant the Rain to Grow Abundance

Foreword by Andy Lipkis

Rainwater Harvesting for Drylands and Beyond Volume 2, *2nd Edition*

Awards

- *Winner, DIY Book Festival – How-To Category*
- *Gold Medal, Living Now Book Awards – Gardening/Landscaping*
- *Silver Award, Nautilus Book Awards – Ecology/Environment/Sustainability*
- *Silver Award of Achievement, Garden Writers Association Media Awards*
- *Finalist, Arizona Book Publishers Association Glyph Award – Reference*
- *Pick, Southwest Book of the Year by the Pima County Public Library*
- *Finalist, USA Book News National Best Book Awards – Gardening*
- *Finalist, Foreword Magazine Book of the Year Award – Home and Garden*
- *Winner, Independent Press Award – Home and Garden*

Praise

"Harvesting rainwater was once a worldwide technology, but was replaced by pipes, canals, and sprinklers: an inefficient and wasteful strategy that results in running dry. In *Rainwater Harvesting for Drylands and Beyond, Volume 2,* Brad uses the concept of 'planting water' as a guiding principle in designing landscapes that passively harvest resources to grow more resources. Such brilliant, low-tech, regenerative systems are vital to hydrating the land and maximizing the benefit that water brings to plants, animals, and people. Thus, this book is an excellent and comprehensive tool for all bucket-and-

shovel 'engineers' to maximize the hydrological resource, reduce energy use, and transform their once-erosive landscapes into ones of stability, botanical diversity, and abundance."
—Arty Mangan, Bioneers Food and Farming Program Director

"This book builds on premises and practices grounded in eons of evolution and adaptation, empowering and inspiring us to use low-cost, natural solutions to solve some of the most pressing needs of dryland communities, and those in wetter climates with dry seasons and droughts."
—Tanya Quist, Director, University of Arizona Campus Arboretum and Associate Professor, School of Plant Sciences

"The original edition was a great book, and this edition is even better! The clear prose and illustrations, the consistently well-organized chapters, the themes and variations, the case studies, the practical design and construction information, the fun can-do attitude—these combine into a manual that is greater than the sum of its parts. Like my copy, you'll have yours dog-eared with abundant use!"
—Dave Jacke, ecological designer, educator, and co-author of *Edible Forest Gardens*

"The cheapest—and sanest—way to meet our growing need for water is to squeeze (or cycle) more out of the water we already have, especially rainwater and used household greywater. Lancaster approaches these unsung streams as a farmer might, cultivating them in order to nourish dry landscapes. He has produced a water-farming guide that will inspire casual gardeners, professionals, and card-carrying permaculturalists. Lancaster is clearly determined to save the world. And he's determined to make it easy for the rest of us to help."
—Hannah Holmes, author of *Suburban Safari: A Year on the Lawn*

"As mayor of a city in the desert southwest, this book is a critical resource to me for implementing strategies that support ecological restoration and community resiliency."

—Emily S. Niehaus, founder of Community Rebuilds and Mayor of Moab City, Utah

"Brad's work is a labor of love for water and life. The breadth, depth, and clarity of this book goes far beyond the usual technical manual. Its deep heart allows these ideas to stick and makes this book a compelling invitation to actively participate. This is a philosophy of life, an offering, made practical in a way that renews life and expands our co-evolutionary engagement."
—Bill Reed, AIA, principal in Regenesis. A founding Board of Director of the US Green Building Council, co-founder of LEED Green Building Rating System, and leader in Integrative Systems Design

"I highly recommend this book to those working hard to be good living ancestors and to those who truly care about the next generations."
—Lilian Hill, Executive Director, Hopi Tutskwa Permaculture

"This is the right book at the right time for a world where water security is one of the most important socio-ecosystemic challenges humanity faces."
— Delfín Montañana, Urban Biologist, Bio·Logica·Urbana consultancy; Director, Socioecological Education, Isla Urbana

"There is nothing like this comprehensive and well-illustrated book about capturing and repurposing rain and other free on-site waters. It's a must-have for every household, policy maker, and professional interested in making their homes, communities, and world more sustainable, self-sufficient, and vibrant."
—Betsy Damon, Founder of Keepers of the Waters

"From Rajasthan to Arizona, Brad learns and teaches, showing how it can be done and why it should be done. Hugely practical and genuinely inspirational."
—Fred Pearce, journalist and author of *When The Rivers Run Dry*

"This very informative book, based on real-life successes, has a very wide application even across the seas. What touches us most are Brad's friendly narration and the 'tell-tale' illustrations that have an eye for detail."
—Shree Padre, Messenger of Rainwater Harvesting, India

"With this book anyone, at any scale of project, can harvest the rain."
—Judy Mielke, landscape architect and author of *Native Plants for Southwestern Landscapes*

"As someone working along with others to directly help refugees and other displaced populations grow more of their own food—often in dryland situations—this book gives us the tools to create lasting change. I carry it in my travel bag wherever I go."
—Thomas Cole, Resilience Design and Agroecology Consultant

"Bridging the gap between DIY and savvy professional work, this is the book everyone should own if they get rainfall in their climate....that means YOU!"
—Matt Powers, educator and author of the *Permaculture Student 2*

See HarvestingRainwater.com for more testimonials and book reviews

Rainwater Harvesting for Drylands and Beyond Volume 2, *2nd Edition*

WATER-HARVESTING EARTHWORKS

Brad Lancaster

Illustrated by
Joe Marshall
Silvia Rayces
Ann Audrey
Gavin Troy
Kay Sather
April Baisan
David Harnish

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To

Everyone featured in this book, the volume preceding it,
and the one to follow, for inspiring and teaching me
by sharing your exemplary, caring lives and actions

All I have connected with, and been hosted by,
on my daily and worldly travels in search of lives
and strategies in balance with nature and community.
You may not be mentioned directly within these pages,
but the teachings from your shared passions
and practices are infused throughout.

All who are actively living the change
they want to see in the world

THE REGENERATIVE FUND

Once production costs are recovered, a percentage of the profits from each book sold will go to the "Regenerative Fund." This money will help fund projects, presentations, and publications that promote rainwater harvesting and other sustainable living strategies. The fund will also be used to help distribute these resources to libraries and schools.

Eight Principles of Successful Rainwater Harvesting

1. **Begin with long and thoughtful observation.**
   Use all your senses to see where the water flows and how. What is working, what is not? Build on what works.

2. **Start at the top (high point) of your watershed and work your way down.**
   Water travels downhill, so collect water at your high points for more immediate infiltration and easy gravity-fed distribution. Start at the top where there is less volume and velocity of water, and it is easier to manage.

3. **Start small and simple.**
   Work at the human scale so you can build and repair everything. Many small strategies are far more efficient than one big one when you are trying to infiltrate water into the soil.

4. **Spread and infiltrate the flow of water.**
   Rather than having water erosively run off the land's surface, encourage it to stick around, "walk" around, and infiltrate into the soil. Slow it, spread it, sink it.

5. **Always plan an overflow route, and manage that overflow as a resource.**
   Always have an overflow route for the water in times of extra heavy rains and, where possible, use that overflow as a resource.

6. **Create a living sponge.**
   Maximize living and organic groundcover—along with life within the soil—to create a living sponge so the harvested water is used to grow more resources, while the soil's ability to infiltrate and hold water steadily improves.

7. Do more than just harvest water.

Maximize beneficial relationships and efficiency by "stacking functions." For example, berms can double as high and dry raised paths. Plantings can be placed to cool buildings in summer. Vegetation can be selected to provide food.

8. Continually reassess your system: the "feedback loop."

Observe how your work affects the site—beginning again with the first principle. Make any needed changes, using the principles to guide you.

Principles 2, 4, 5, and 6 are based on those developed and promoted by PELUM—the Participatory Ecological Land-Use Management association of east and southern Africa. Principles 1, 3, 7, and 8 are based on my own experiences and the insights gained from other water harvesters.

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Foreword

By Andy Lipkis

Superheroes are what happens when any among us link hands, say we care, and take smart, effective action.

"G'day! How yur tanks?" This four-word greeting changed my life. Twenty-one years ago while traveling up the east coast of Australia with my wife and infant daughter, I noticed that nearly every conversation between rural Australians began with this question.

Instead of the automatic, "How are you?" or "Nice weather," it was a specific question that— once I figured out what it meant—spoke volumes about these people's connections: to the land, to each other, and to the environment.

Tanks, also known as cisterns, are the very large containers that store captured rainwater and provide rural Australians with their life support: vital water for drinking, bathing, and gardening. Many rely exclusively on captured rainwater for all their needs.

This one question bundled and abbreviated a collection of concerns: How is your water supply holding out? How has the rain treated you? How are you doing in managing your land and water? How is your family holding up? At what state of readiness do we need to be for our community today?

Having spent much of my life working to awaken people's awareness and inspire them to take personal responsibility for the environment, I was thunderstruck at the advanced state of consciousness being expressed by these Aussies, and I saw in that awareness an answer to the water crisis facing cities in my native Los Angeles, as well as in arid and non-arid lands around the world.

And for that same reason, I congratulate and thank you for picking up this book. You wouldn't be reading this if you didn't have an awareness of the need to take responsibility and action either to secure your own water supply or help

solve the larger looming problems. Whether you are in it for selfish or selfless reasons, you are a pioneer and taking on the role of environmental healer. You are an early adapter to a world that is already experiencing ever-increasing water and energy issues because of climate change and other issues.

Your experience, persistence, and success in this new wave of rainwater harvesting may lead the way to wide-scale systemic adoption and implementation in cities around the world.

Rainwater capture is transitioning from an individual act of personal survival and self-reliance, to one that is replanting seeds of community, interdependence, resilience, and sustainability.

The local and global world water situation is becoming urgent. As humans in first-world nations, our consumption and waste of natural resources is generating sufficient pollution and depletion to damage and impair the healthy functioning of nearly every natural system on earth. These ecosystems are our life-support infrastructure for clean, abundant, and safe water, as well as food, oxygen, and a stable climate. Reversing the degradation requires a profound transformation of individual and communal perspective and behavior.

Instead of believing that government and centralized systems are in charge of the environment, we must shift to the other end of the spectrum where individuals, families, households, neighborhoods, villages, and towns take personal and collective responsibility for repairing and maintaining the ecosystem and its natural life-support systems, with government providing guidance and support.

As you read this book, you'll find that rainwater harvesting practiced as prescribed herein is really watershed and ecosystem stewardship. In sculpting your landscape and creating water-capture systems, you will be restoring, revitalizing, or mimicking natural systems such as forest watersheds. As such, you'll be repairing the ecosystem and laying the foundations of your community's sustainability. And you will be a leader. Any change you make on your home can become a demonstration and model that others—your neighbors, elected officials, and government agency staff—will be able to study, copy, and evolve.

As president of TreePeople, a nonprofit organization I founded 37 years ago, I like to say that we are helping nature heal our cities. Our work is to inspire

people to take personal responsibility and participate in making their cities sustainable urban environments. Our prime focus is to support people in designing, planting, and caring for *functioning community forests* in every neighborhood in Los Angeles (at the time of this writing, one of the world's least sustainable megacities).

Forests are natural sustainability infrastructures. Trees are *the* basic earthworks. Trees and forests, and the highly porous and mulched soil beneath them, capture, slow, filter, store, and recycle rainwater, and thereby recharge streams, groundwater aquifers, and springs. They provide protection from droughts, floods, and pollution—cleaning the water so it's drinkable and usable. Trees and forests sustain life. Unfortunately, when most cities were created, the land's original watershed functionality was unwittingly destroyed. The idea behind functioning community forests is to plant trees and manage the land in cities in a way that mimics natural forests, bringing water, protection, and resources back to urban residents. However, since urbanization has sealed so much of the land with buildings, roads, and parking lots, simply planting trees and creating green spaces often isn't enough to make up for the lost watershed. By adding water-harvesting technologies that are designed to mimic nature, such as earthworks (rain gardens, swales, sheet flow spreaders, and others) that are integrated with cisterns, on-site gravity-fed greywater systems, and clearwater recycling/reuse systems, it is possible to replace the watershed and ecosystem functions that were lost.

The magnitude of the water crisis—and the opportunity—became clear to me in 1992, when the U.S. Army Corps of Engineers proposed to spend half a billion dollars to increase the capacity of the Los Angeles River by raising the height of concrete walls along its banks. The Corps determined that the Los Angeles area had been so overpaved that, instead of soaking into the ground, rainwater from a 100-year storm event would rush off the paved and sealed surfaces so quickly that it would overwhelm the river and flood the nearby cities of southern L.A. County.

It was at that moment that the "How Yur Tanks?" lessons clicked for me. I wondered how much of our 14.7 inches (373 mm) of average annual rainfall we were throwing away each year, and whether we could use that half-billion dollars for cisterns to capture and use that precious rainwater, just like the

Australians do. I asked the county's flood control engineers and they dismissed the idea, stating that replacing the river walls would require installing a 20,000-gallon (75,700-liter) tank at each of one million homes—an expensive and impossible task. The local water supply and stormwater quality agencies had similar responses to my questions. The idea was too expensive for their individual missions and budgets and would require what they considered to be completely unacceptable lifestyle changes on the part of the public. In the process of these discussions, however, I learned that our average rainfall, if harvested and used appropriately, could replace the portion of our imported water that we use for landscape irrigation—roughly half of the one billion dollars' worth of water the city of Los Angeles IMPORTED every year.

What seemed impossible to the agencies was perfectly logical to me. I researched and found out that the separate water-related agencies had separate, unconnected plans to spend a combined $20 billion in the next decade or so to upgrade or repair their respective systems, yielding only "band-aids" with no overall improvement in sustainability of the region.

So, I began designing a 20,000-gallon (75,700-liter) cistern that could safely fit in a small urban yard without compromising anyone's lifestyle or posing any threat during our occasional earthquakes. It turned out to be a modular 2-foot-wide, linear, recycled food-grade plastic tank that could replace the fence or wall that separates most urban and suburban residential properties—with overflow directed to a water-harvesting landscape. Further, I proposed to outfit all the tanks with wireless remote-controlled valves and pumps that would enable flood-control, water-supply, and stormwater-quality officials to centrally manage the multitude of independent tanks as one highly adaptable storage network.

The networked mini-reservoirs of tanks and earthworks could thereby perform at least triple service for potentially less money than all the agencies' separate projects. By also adapting all the areas' landscapes to become functioning community forest watersheds, my system was intended to produce multiple additional benefits such as creating tens of thousands of new green-collar jobs, saving copious amounts of electricity (by reducing air-conditioning needs with well-placed shade trees AND reducing the pumping required to import water over the mountains into Los Angeles), reusing all garden and

landscape biomass and prunings on site as mulch, creating a new local plastic recycling industry product and market, and creating a disaster-resilient backup local water supply.

This was a lovely and compelling vision, but no one in an official capacity took it seriously. I realized I'd need to do something to prove that the idea was feasible, both technically and economically. That notion turned into a six-year program of design, feasibility, and cost-benefit analysis that became known as the T.R.E.E.S. Project (Transagency Resources for Environmental and Economic Sustainability). It involved hundreds of engineers, landscape and building architects, foresters, scientists, and economists who collaborated to create a book full of designs and specifications (Second Nature, TreePeople, 2000) to retrofit or adapt every major land use in Los Angeles to function as urban forest watersheds. Other team members spent two years conducting a rigorous cost-benefit analysis. And finally, we built a demonstration project, adapting a single-family home in South Los Angeles.

The demonstration site, known as the Hall House (named for its owner, Rozella Hall), had a relatively simple set of interconnected earthworks designed to capture, clean, store, and use rainwater from a massive storm event, and prevent any of the rainwater or biomass from leaving the property and thus being wasted. We built berms around the lawns, installed a mulched swale, put in a diversion drain to pick up driveway runoff and carry it to a sand filter under the lawn, fabricated and installed two modular 1,800-gallon (6,800-liter) fence-cisterns which were fed by rooftop rain gutters through a filter, then connected to the irrigation system, and finally, planted a trellis "green wall" of climbing roses to shade and cool the house's sun-heated south-facing wall. We also removed 30% of the lawn and replaced the remaining turf area with drought-tolerant grass.

Then, on a hot August day in 1998, we invited our agency partners, numerous public-works officials, and the news media to see the demonstration house. We handed them umbrellas and unleashed a 1,500-year flood event via a fire truck, pumping and spraying on that one house 4,000 gallons (15,100 liters) of water in ten minutes. Officials huddled in stunned silence as they watched the water fall and flow, pooling in the bermed lawns and cistern. They saw that none of the water flowed to the street and storm-drain system. They

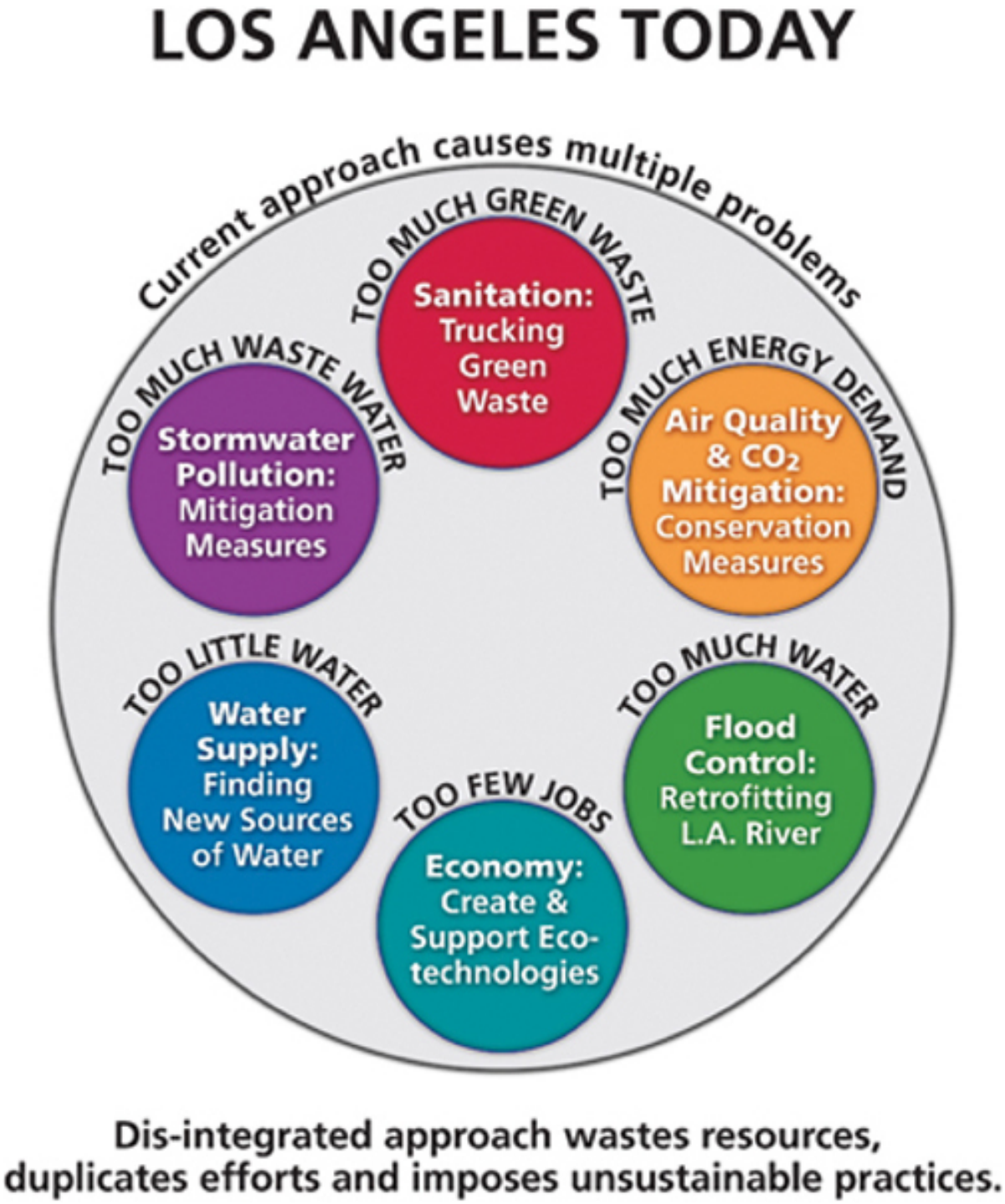
saw how, in that one instant, their annual billion-dollar burdens of separate infrastructure systems and needs were elegantly bundled and handled. The result: no stormwater pollution, no street flooding, no green waste, dramatic water and energy savings, more attractive landscape, and potentially thousands of new jobs.

The head of L.A. County Public Works' flood control division couldn't contain his enthusiasm and proclaimed that the simple elegance meant this demonstration could be easily replicated. A day later, after he and his staff reviewed both our engineered designs and cost-benefit analysis, he called me: "I'm sorry. We didn't understand. We think you've cracked it. Your idea needs to be deployed throughout the whole county, but it's going to cost more and take more time than you think. But despite that, we need to begin scaling this up immediately. We'd like to try this idea to solve one of the county's most persistent urban flooding problems."

That was the beginning of the Sun Valley Watershed project, located in the City of Los Angeles' San Fernando Valley. After a successful two-year feasibility study, the County Public Works Department launched a thorough "stakeholder-led" watershed-management-planning and environmental-impact analysis. Six years later, both the plan and environmental report were approved; construction of the first project began within a few weeks. The plan calls for the retrofit of 20% to 40% of the watershed's 8,000 homes and their landscapes, and installation of a diverse network of earthworks. The earthworks mix ranges from simple to complex, beginning with tree planting, pavement removal, mulching, and berming. On the more complex end, the projects include installing street swales, and school watershed parks that replace asphalt play yards with permeable green-spaces above large underground infiltration systems and cisterns.

The Sun Valley Watershed planning process informed and transformed many of the participating agencies and organizations and inspired others who followed the process. For example, Los Angeles County Public Works formed a new, integrated Watershed Management Division. The City of Los Angeles Bureau of Sanitation launched and completed its first ever Integrated Resources Plan for Water. And among several cities outside the Los Angeles area, the City of Seattle initiated its Salmon Friendly Seattle program, which

seeks to restore viable salmon habitat throughout the metropolitan area by revitalizing watershed and forest functionality in all the city's neighborhoods.


LOS ANGELES TODAY
Current approach causes multiple problems
TOO MUCH GREEN WASTE
Sanitation: Trucking Green Waste
TOO MUCH WASTE WATER
Stormwater Pollution: Mitigation Measures
TOO MUCH ENERGY DEMAND
Air Quality & CO_2 Mitigation: Conservation Measures
TOO LITTLE WATER
Water Supply: Finding New Sources of Water
TOO MUCH WATER
Flood Control: Retrofitting L.A. River
TOO FEW JOBS
Economy: Create & Support Eco-technologies
Dis-integrated approach wastes resources, duplicates efforts and imposes unsustainable practices.

There are several keys to the projects' successes so far:

1) we demonstrated that these adaptations represented *acceptable and attractive* lifestyle changes that would be politically palatable;

2) we demonstrated with rigorous engineering that they were technically feasible, safe, and capable of solving pressing problems;

3) we demonstrated that they were economically feasible by identifying multiple outcomes and benefits that altogether would over time save money for the assembled funding partners; and

4) we engaged and educated all the stakeholders from both the community (including children) and relevant agencies.

This story is far from over. As it continues to unfold it presents a variety of political, jurisdictional, and regulatory issues and problems that we work to resolve. My initial vision was that so much water and money could be saved by local governments that agencies would help individuals and businesses cover the costs of installing and maintaining the systems on their properties. That is now happening in some cities, such as Santa Monica, Seattle, and Houston, which are giving grants for cisterns and water-saving landscapes.

As we confront growing water-quality and supply issues, plus the increased threat of flooding and weather-related calamities, it is increasingly urgent that we find ways of adapting our homes, neighborhoods, towns, and cities to become resilient to climate change and disasters. You have a huge role to play in protecting your household and region by personally implementing some of the water-harvesting practices detailed in this book. If you do this, and make yours a demonstration project, you will help prove that it is feasible and attractive for your region. You will make it more politically palatable, so your local politicians can pass laws, change ordinances and codes, and make resources available to help others implement on a wide scale. And then, collectively, we just might tip the balance and put our nation on the road to a healthy, just, and sustainable future.

Dig in and have fun.

—Andy Lipkis, 2008

Andy Lipkis is Founder and President of TreePeople, a Los Angeles-based social-profit organization that he founded in 1973. Andy collaborates with leaders, cities, businesses, and agencies to identify and implement natural-systems-based solutions to human, social, and infrastructure problems. He co-wrote, with his wife and partner Kate, The Simple Act of Planting A Tree: A Citizen Foresters' Guide to Healing Your Neighborhood, Your City and Your World, and has been recognized and honored as one of the founders of the Citizen Forestry movement.

Update, 2019

A lot has happened in the past 11 years that both underscores the urgency of taking action to become climate resilient, and validates the viability and scalability of the solutions in this book. These solutions are among the most immediately accessible and powerful paths to making our homes and communities safe, healthy, fun, inspiring and sustainable.

The growing intensity of severe and extreme climate events appear to be mimicking early stages of the cascading ecosystem and civil society declines that led to the disappearance of a number of past civilizations, as documented by Jared Diamond in his book *Collapse*. Diamond asserts that every civilization throughout human history that forgot its forests, and cut them down without replacing them, triggered loss of soil, local water, food, and a cascading decline of ecosystem and human life-support services, and ultimately disappeared. In contrast, every civilization that noticed the decline and acted to re-establish the trees and protect them, re-established its water, soil, food, and protection from severe weather and social breakdown...and saved themselves. It is not too late. Despite the overwhelming magnitude of these problems, there are actions we can take as individuals and communities to both combat the causes, and adapt our homes, neighborhoods, and cities, to make them much more resilient to these threats.

We urgently need to capture the rain when it falls, to *re-hydrate* the soil and re-enliven it with more vegetation, microorganisms, and other life. Hydrated, enlivened soils sequester carbon, recharge aquifers, and rebuild the atmospheric short-water cycle, which some hydrologists and climatologists believe will moderate severity and help mitigate the problem.

In California, our demonstration projects, along with others, did indeed build political support, resulting in new laws, programs, and funds which slowly but steadily are enabling the wide-spread scaling of these ideas. LA city's Department of Water and Power created a Stormwater Capture Master Plan identifying rainwater capture as a source for 45% or more of its local needs. LA area agencies then collaborated with TreePeople to co-design and build a pilot demonstration project wherein 6 homes were retrofitted with rainwater harvesting landscapes, and equipped with remote-controlled and jointly monitored and managed cisterns. That pilot, known as "*LA Stormcatcher*" showed the benefits of wide-scale adoption. Los Angeles County voters have

just approved a property tax to provide $300 million per year to build *and maintain* rainwater capture and treatment facilities as part of green infrastructure, to both clean up storm-water pollution and increase local water supplies.

During the decade-long "millennium drought" in Australia, numerous changes to water use practices and policies, along with generous financial incentives, resulted in unprecedented numbers of Australians installing residential rainwater cisterns at their urban and suburban homes, (30% of the homes in Sydney and Melbourne, and 50% of the homes in Brisbane and Adelaide), dramatically changing their lifestyles, and cutting water use in half —thus enabling the country to make it through the drought crisis. When the drought ended, most people retained their cisterns, and many added more storage capacity and advanced treatment. Then, in 2009, in the wake of massive, unstoppable, deadly, and devastating wildfires—similar to those in California—new building codes were adopted requiring homes *in urban-wildland* interface areas to have tanks with at least 5,000 gallons of water on hand for firefighting. This decentralized water supply was needed because the centralized water systems were found to be vulnerable and insufficient to fight the fires.

We need *superheroes* to quickly stand up and save us. These superheroes are us, our trees, and our shared ecologies! We are it! We have the power to choose and take action immediately. Superheroes aren't just a few macho strong men and women. Superheroes are what happens when any among us link hands, say we care, and take *smart, effective action*. That's community—caring, collaborative, powerful—like the community of life that is a native oak tree.

The minute an acorn (an oak seed) sprouts, before it sends leaves, it puts down a root as far as nine feet (3 m) deep to establish a stable water supply. From there it starts to transform the ecosystem and attract and support all kinds of additional life forms that it relies on to thrive and grow to a 100-foot (30-m) diameter canopy. This massive living organism—one of the largest on the Earth—could not function without the thriving community of earthworms, mycorrhizal fungus, and other tiny critters that live in the soil underneath the tree.

That tree cannot drink unless billions of microscopic fungi hand individual molecules of water to the trees' roots (for which the tree gives the fungus photosynthesized sugars in thanks). This collaboration might make you ask, "Who's more *powerful* in this equation—the largest or the smallest life forms?" But its not about that kind of power—its not about competition. This is a collaborative space where we all need each other. Everything's happening because life forms are communicating and collaborating.

The oak and its community become a kind of a sponge, with huge capacity to capture water in the massive canopy and the root network of the tree. The rainwater drips slowly through the canopy to the ground below, where the decomposing leaves, mulch, microbes, critters, and animals in the soil capture it and work together to clean and treat it, then they slowly release surplus stormwater in a calm and productive (not flooding and erosive) manner to the watershed and the aquifer. Just one tree and its soil-borne community is a 120,000-gallon (454,000-liter) living cistern, living fire protector, living air conditioner, living flood abatement strategy, and living water treatment facility.

Now is a great time to discover and embrace your inner superhero. You are just like the oak tree community. Plant water and catch water. Plant trees and grow collaboration, fun, and resilient strength with family, friends, and neighbors.

—Andy Lipkis, 2019

Preface

We ain't dry. We just leakin'.

—Janet Millington, Australian permaculture teacher referring to a lack of water harvesting and conservation compounding droughts in Australia

"You've got to plant the water before you plant the trees." An African water-farmer named Mr. Zephaniah Phiri Maseko told me this. "Create a water plantation by planting the rain," he said. "Plant it here, there, over there, everywhere, so it will germinate everywhere!"

I looked across a diversely vegetated landscape. It was something of a miracle. This area in the dry region of Zvishavane, Zimbabwe, (average annual rainfall 22 inches, or 559 mm) was once highly degraded and eroded. But Mr. Phiri had turned a wasteland into an oasis by controlling erosive runoff, harvesting the rain, and planting it within the soil. He and his family did it by creating a diverse array of water-harvesting earthworks such as infiltration basins, terraces, berm 'n basins, check dams, diversion swales, and contour plantings throughout their 7.4-acre (3-hectare) site (figs. P.1, P.2).

Fig. P.1. Mr. Phiri in the hand-dug reservoir he calls his "immigration center" located on the highest point of his site, where he has a good amount of soil. "Rain, welcome to my country!" he shouts during storms. "Now I will tell you where you will live: in the soil!"

Fig. P.2. Mr. Phiri tending his tree nursery. He gives hundreds of trees a year to fellow community members to vegetate the watersheds, build water-absorbing soil, and grow more resources. "People must plant the water before they plant the trees," he says. Water is planted with water-harvesting earthworks.

Following the simple principles of water harvesting, they began at the top of their watershed and continued all the way to the bottom. Now more water was harvested within their soils than was extracted from them by pumping out groundwater, or by evaporation and plant uptake. They gave the land more than they took. As a result, Mr. Phiri's well levels and those of his immediate neighbors began to rise slowly. Erosion was in check, soil was accumulating, fertility was increasing, and the family's farm could now support the family for the long-term. Scarcity had been turned into abundance.

As I walked around Mr. Phiri's land, I felt excited and hopeful. Here was a living, thriving example of a site, stewarded by people, that was improving with time! Progress was happening without degrading the lives or environments of others! For too long I had observed too many gardens, yards, farms, neighborhoods, ranches, and communities degrading with time. Many appeared to be doing great on the surface, but when I looked more closely I realized they were consuming more resources (water, energy, time, money, soil fertility) than they were producing. They were taking more resources from their local economies, ecosystems, and communities than they gave back.

So it was in my hometown of Tucson, Arizona. Growth was booming but we had contaminated our aquifer, depleted groundwater supplies, run our rivers dry, and killed countless springs and wells. Then we took water from other regions using elaborate canal, pump, and water-right buyout schemes at great financial and environmental cost to feed our constantly growing demand for water. Tucson was killing itself— or at least its water resources and those of others. And everyone who lived in Tucson—everyone who drank, irrigated, built, bathed, and washed with water—was part of that problem. But I didn't want to contribute to the problem. I wanted to leave. I wanted to run (figs. P.3, P.4A, P.4B).

Fig. P.3. Matt Weber kayaking his flooded neighborhood street in Tucson, Arizona. The bulk of the rain falling on the city's private and public landscapes (where it would be a free resource) is quickly drained to the streets and storm drains, where flooding is a costly liability.

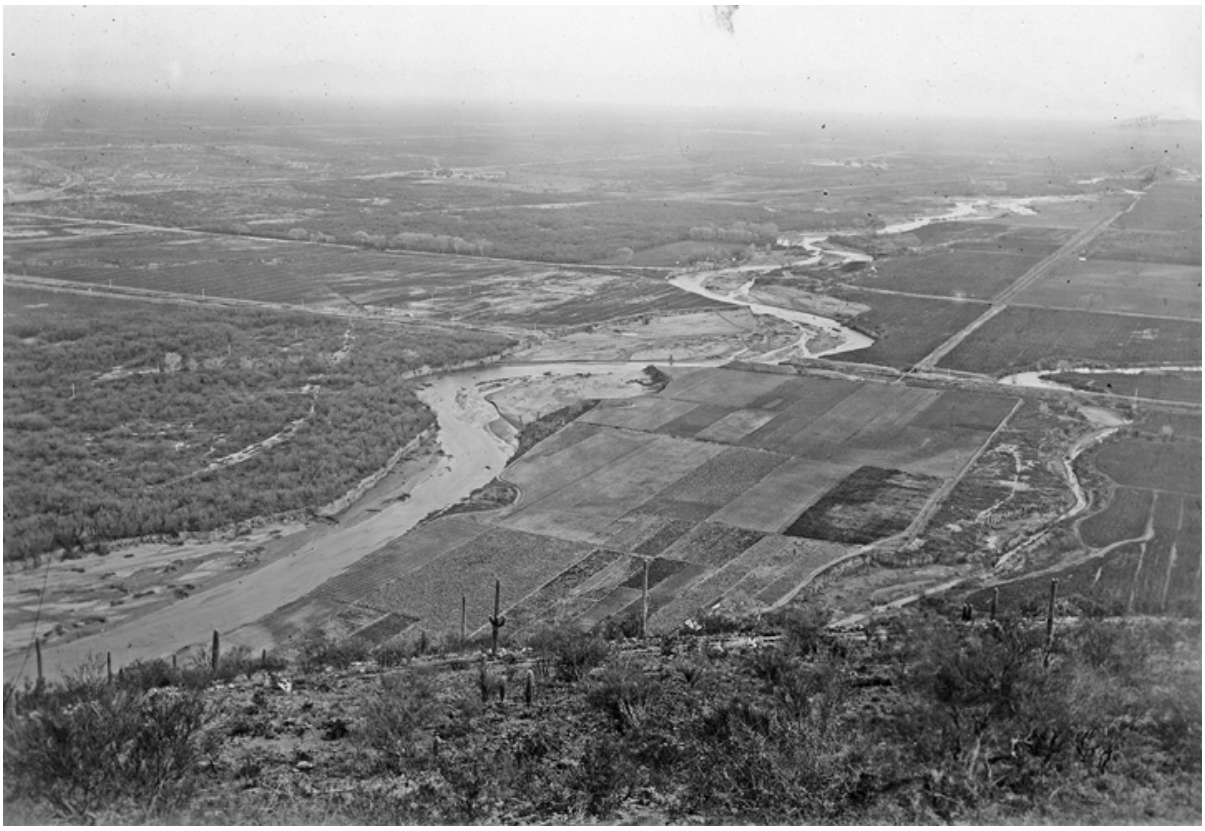


Fig. P.4A. The Santa Cruz River in Tucson, Arizona, looking southeast from Sentinel Peak in the early 1900s. Note the meandering, flowing river and the rich sponge of vegetation throughout the watershed (especially where the native tree forests have not yet been replaced by agricultural fields). Such a watershed absorbs more rainfall than it drains. Water moves more slowly and consistently through the forested watershed and the meandering waterway. Courtesy of Arizona Historical Society/Tucson BN 203, 274

Fig. P.4B. The same stretch of the Santa Cruz River in 2017. Note the dry, channelized riverbed and how much of the watershed's vegetative sponge has been replaced with pavement, buildings, or bare compacted earth. The watershed now drains more rainfall than it absorbs. During storms, flooding water erosively rips through the watershed and straightened river channel unchecked to cause flooding problems downstream. And summer temperatures are rising due to the heat absorbed within the exposed pavement and bare soil.

"If we run from our problems, they follow us," Mr. Phiri said, when I told him of my dilemma. "But if we root ourselves and face our problems we solve them."

I then realized the concepts and the strategies Mr. Phiri had used could easily be replicated or adapted elsewhere, such as my hometown. I excitedly returned home, rooted myself, and adapted Mr. Phiri's concepts and strategies in my yard, at my clients' sites, and in neighborhood projects, all with wonderful results.

At our Tucson, Arizona homes (receiving 12 inches or 305 mm of average annual rainfall), each year my brother, sister-in-law, nephew, and I now typically harvest about 100,000 gallons (378,500 liters) of rain and runoff in the soil of our shared 1/8-acre (0.05 ha) urban oasis and surrounding public right-of-way.

We've been consuming just 20,000 gallons (75,700 liters) of municipal water a year to meet our household needs and provide water to our washing machine, which serves as a community greywaterharvesting laundromat (see our story in Real-Life Examples in chapter 12). Though I've since set up my home to meet 95% of its domestic (indoor) water needs from rain harvested off just 400 square feet (37 m^2) of roof (see chapter 5 in Volume 1 for more). Ninety-five percent of the landscape's, orchard's, and garden's water needs are supplied by a combination of harvested rainwater and greywater, which consists of recycled "wastewater" from all household drains except the toilet. Our once-barren lot is now a lush landscape that produces 15% to 25% of our food, passively heats and cools the home, enhances urban wildlife habitat, and has won numerous awards for water conservation and artistry.

This book documents a diverse array of successful sites where passive water-harvesting earthworks serve as the foundation of thriving landscapes. You can accomplish similar successes at home and beyond by simply building on the skills you already have and using common sense. Mr. Phiri had only a 6th grade education when he taught himself to harvest the rain. Now his work at home, in his community, and throughout southern Africa inspires a new generation of water harvesters. The key to Mr. Phiri's success (and mine) was following eight principles of successful rainwater harvesting, and three ethics.

EIGHT PRINCIPLES OF SUCCESSFUL RAINWATER HARVESTING

1. BEGIN WITH LONG AND THOUGHTFUL OBSERVATION

Fig. P.5. Observe where the water flows, where it collects, where it drains away, and where it drains from. This informs you of your resources and challenges. What is working? Build on that. What is not working? Change it.

2. START AT THE TOP (HIGH POINT) OF YOUR WATERSHED AND WORK YOUR WAY DOWN

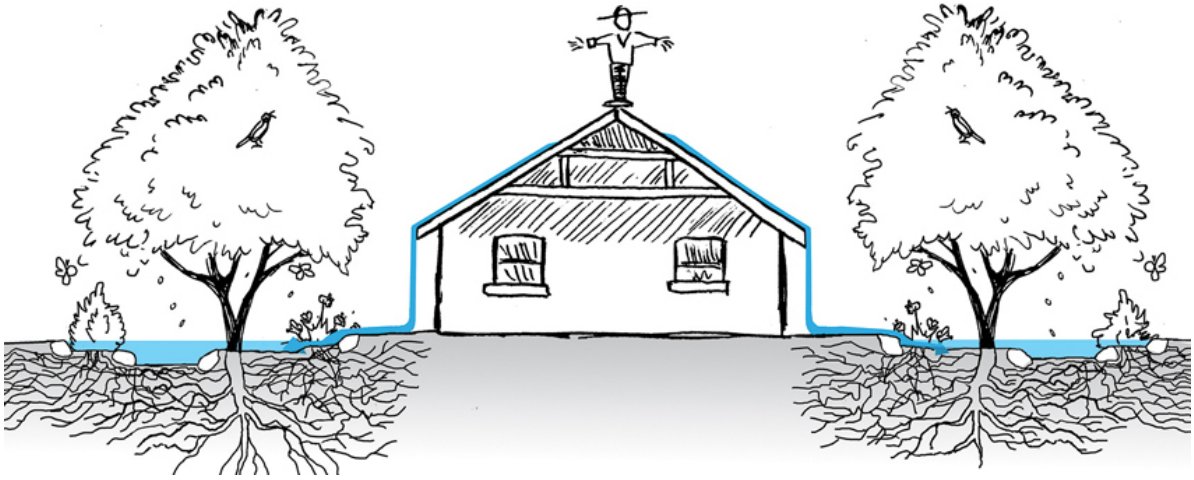


Fig. P.6. It is easier to harvest water high in the watershed than low in the watershed because the volume and velocity of flow is less, and more manageable, at the top. And you can then use the free power of gravity to distribute the harvested water to areas downslope.

3. START SMALL AND SIMPLE

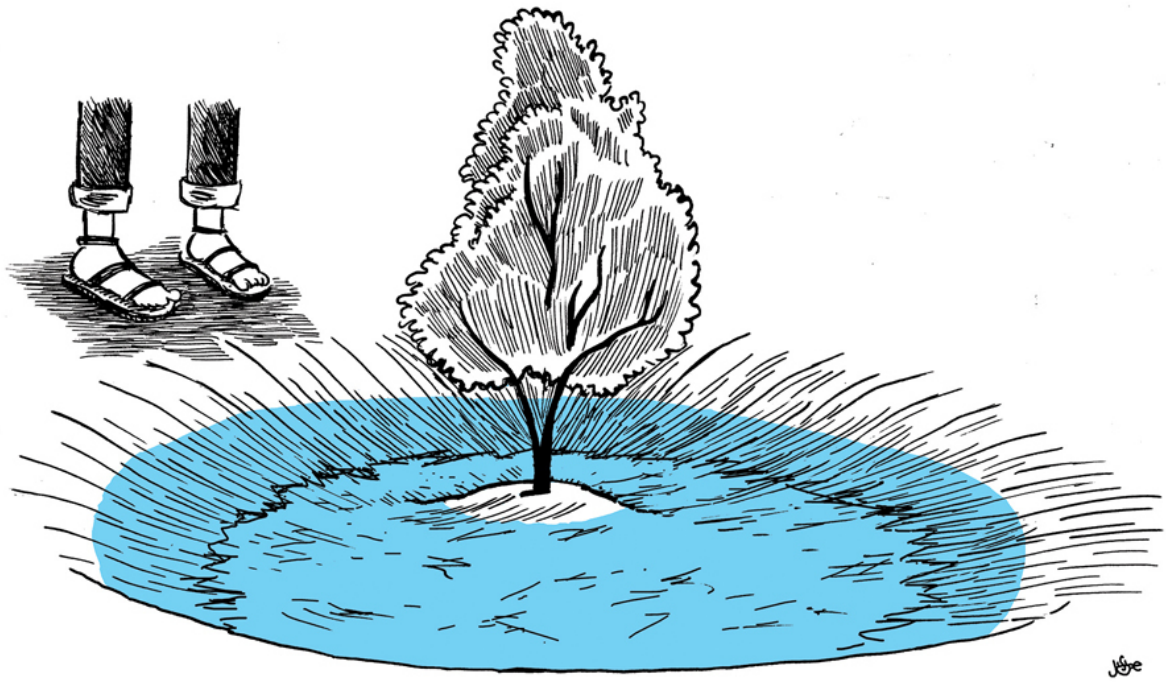
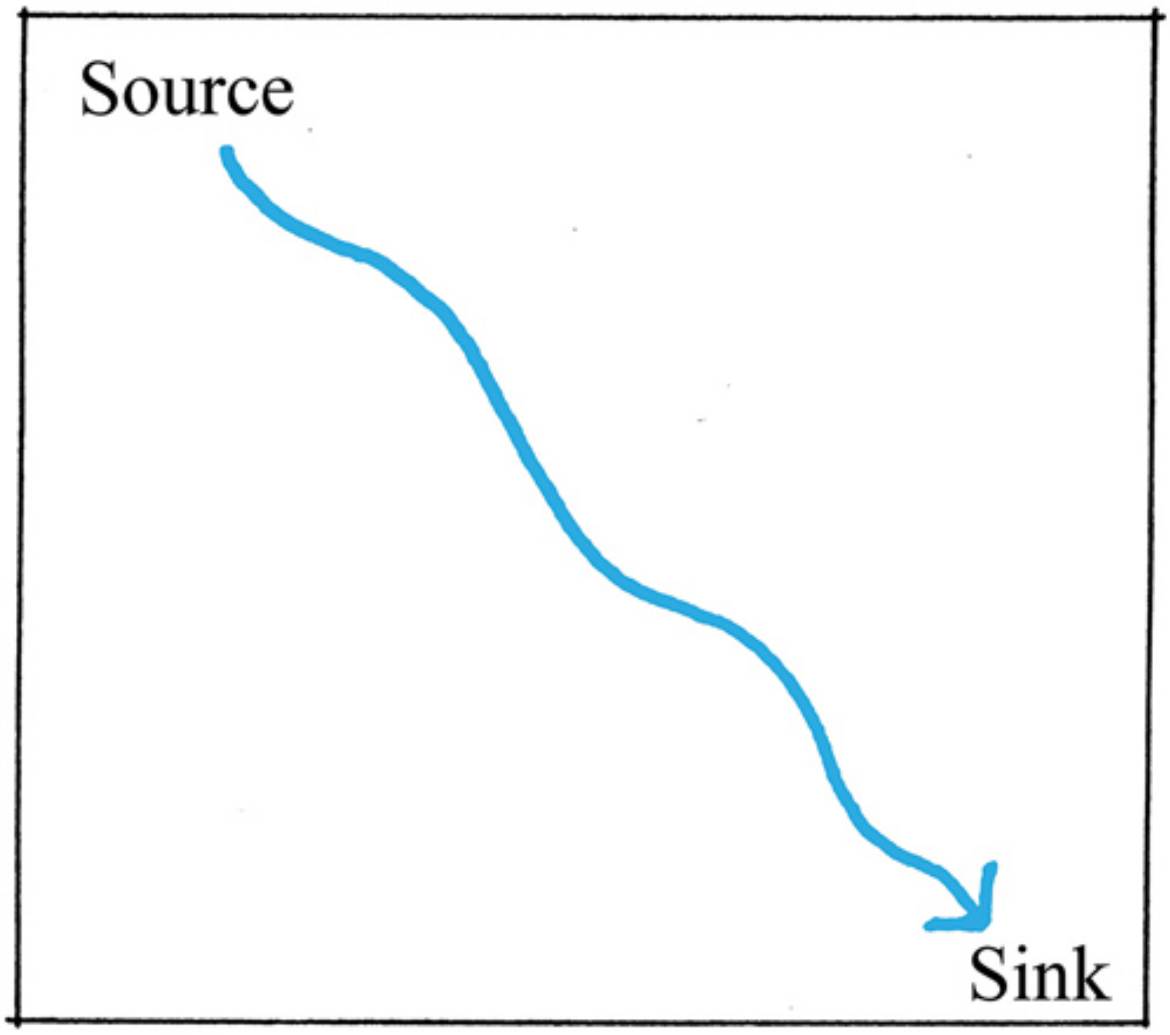


Fig. P.7. Small, simple systems of appropriate scale are easier to create and maintain than complex, extensive systems so starting small and simple makes it all more fun. As an added benefit, large numbers of small earthwork structures distributed throughout a watershed will be far more effective at hydrating the land than a small number of large-scale earthwork structures in just a few areas of the watershed.

4. SLOW, SPREAD, AND INFILTRATE THE FLOW OF WATER


Source
Sink

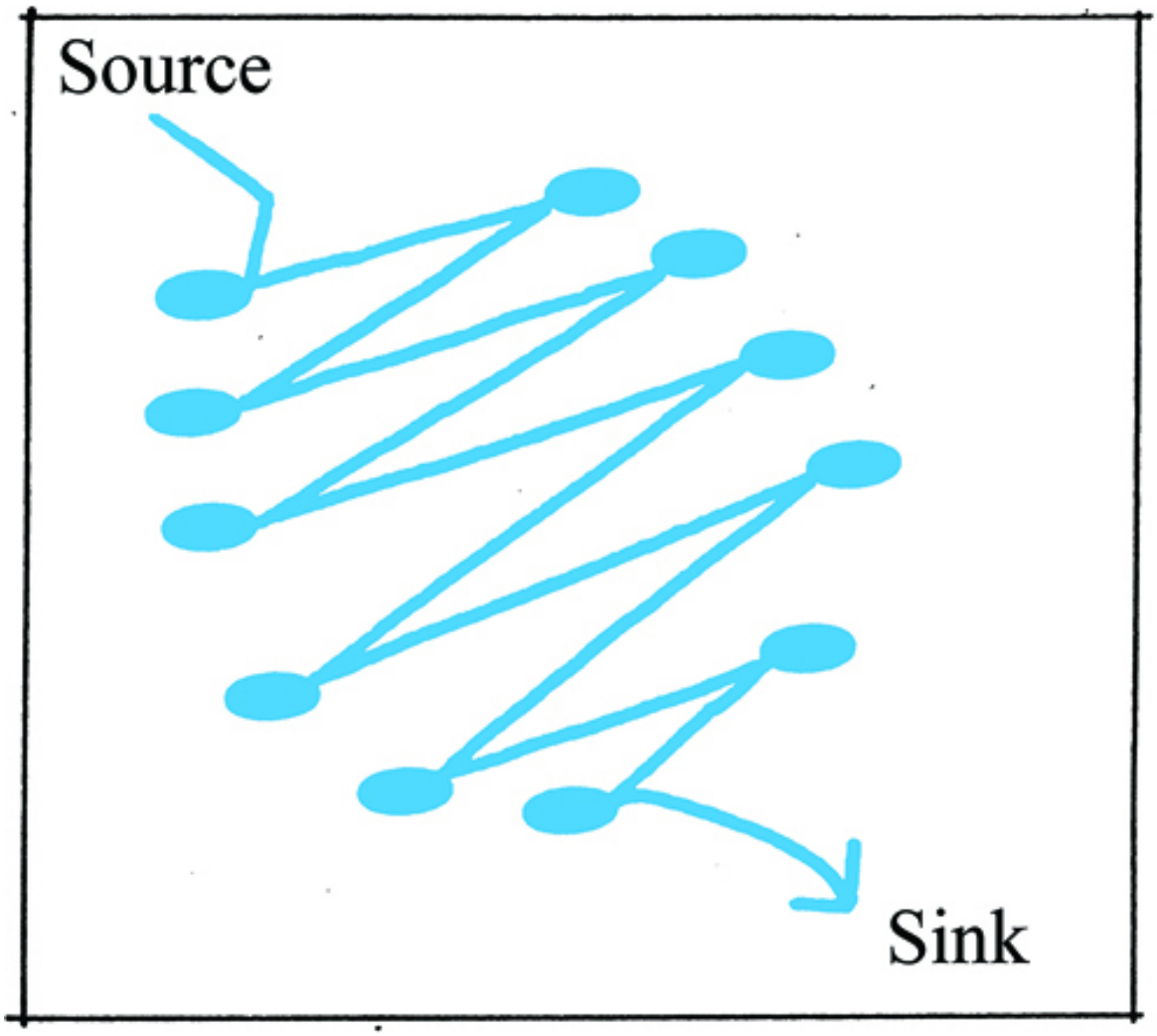


Fig. P.8. Top image: water flow rapidly dehydrating the landscape. Bottom image: water flow effectively rehydrating the landscape. Zig-zag and calm the flowpath of water to reduce destructive erosion and increase the time and distance the water flows. This will increase infiltration into the soil from source (high point) to sink (low point). This practice achieves waterspread throughout the watershed.

5. ALWAYS PLAN AN OVERFLOW ROUTE, AND MANAGE THAT OVER-FLOW AS A RESOURCE

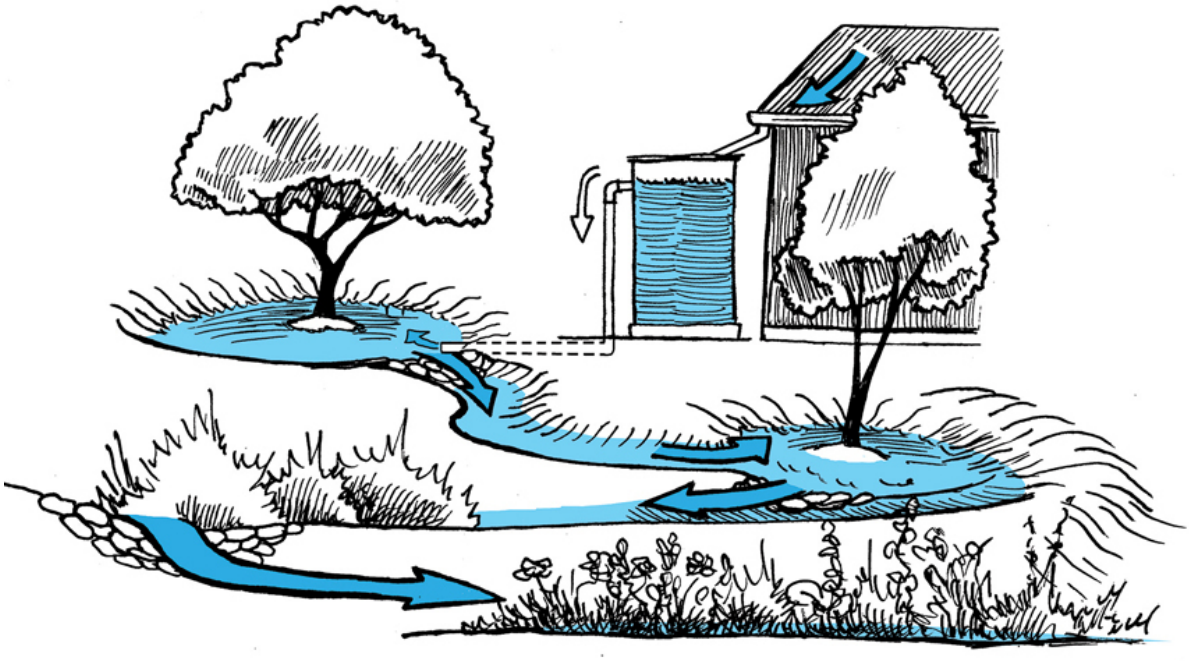


Fig. P.9. You can't turn off the rain once your water-harvesting earthworks and cisterns are filled up, so always be prepared for overflow. In this case, cistern overflow water is designed to fill a nearby, vegetated earthwork, then overflow to the next earthwork, and the next, as it passively irrigates sheltering vegetation. The zig-zagging flowpath also follows the fourth principle–slow, spread, and sink. Arrows denote runoff flow.

6. CREATE A LIVING SPONGE

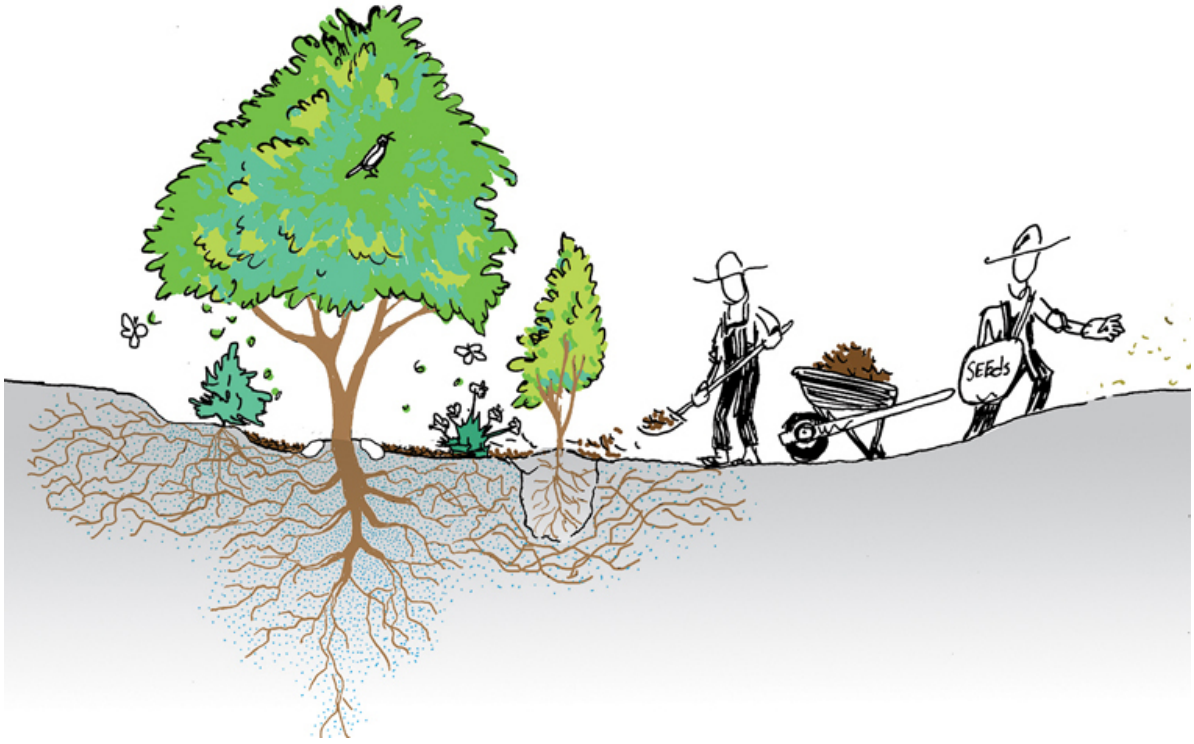


Fig. P.10. Maximize planting of climate-appropriate vegetative groundcover, spread organic mulch over the surface of the soil, and encourage more beneficial life within the soil to create a "living sponge" that uses harvested water to grow more resources. As roots expand and soil life increases, the soil's ability to infiltrate and hold water steadily improves.

7. DO MORE THAN JUST HARVEST WATER

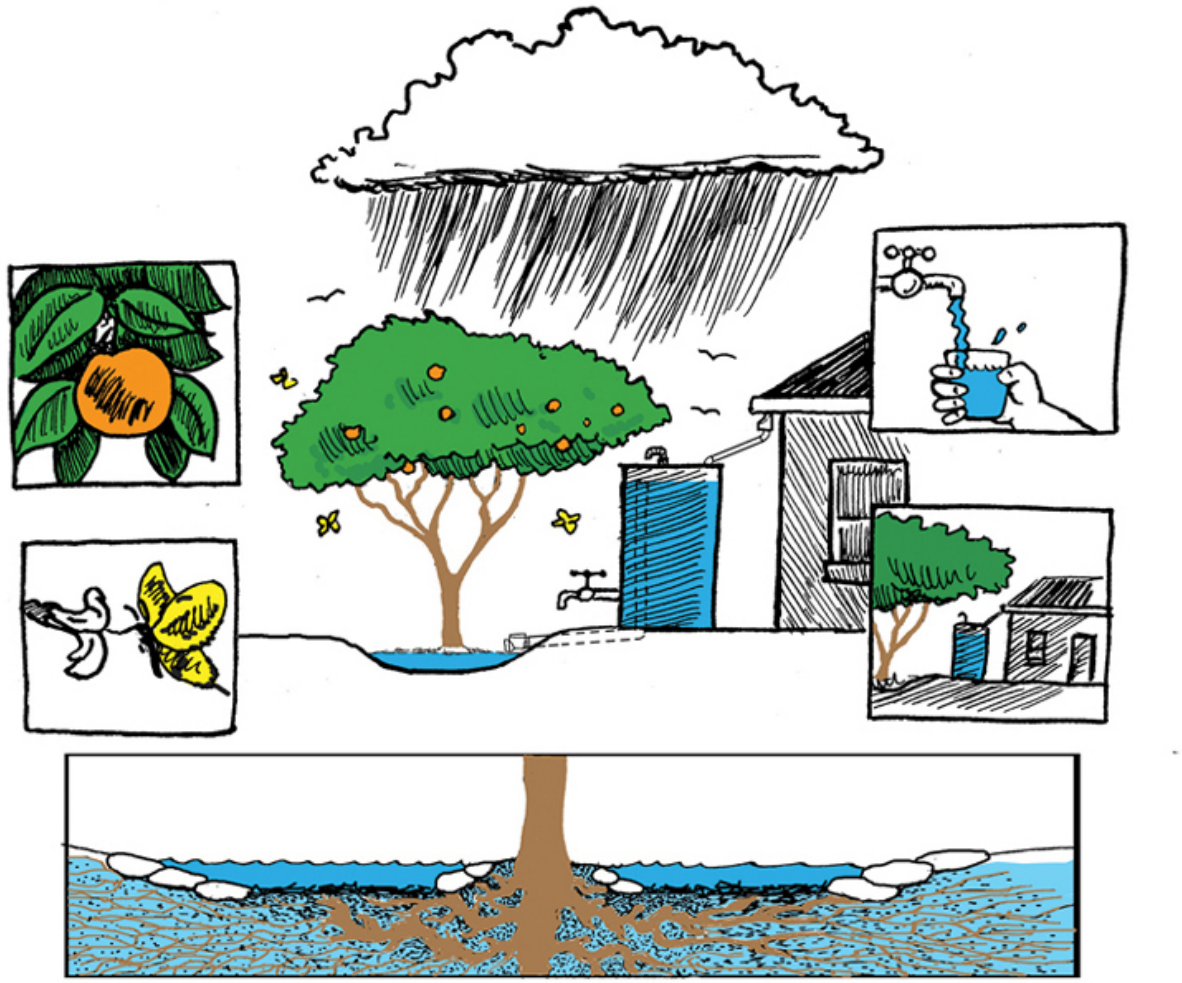


Fig. P.11. Maximize beneficial relationships and efficiency by "stacking functions." For example, cisterns and earthworks provide high quality irrigation water and serve as on-site stormwater control strategies. In turn, rain-irrigated vegetation and above-ground cisterns can passively shade and cool the east and west sides of buildings in summer, while the plants also clean our air, produce food, create wildlife habitat, and add beauty to our lives.

8. CONTINUALLY REASSESS YOUR SYSTEM: THE "FEEDBACK LOOP"

Fig. P.12. The value of long and thoughtful observation extends throughout the life of your system. How is the land responding to your work? How are your strategies performing? What still needs to be addressed? Make any needed changes using all the principles to guide you.

WATER-HARVESTING ETHICS

The following three ethics further increase the benefits of water harvesting on your site and well beyond. They are the ethics of permaculture,[1] a methodology of integrated, sustainable design based on natural systems.

1. The CARE OF THE EARTH[2] ethic reminds us to care for all things living and nonliving, including soil, water, air, plants, animals, and entire ecosystems. As I

Mollison states in *An Introduction to Permaculture*, "It implies harmless and rehabilitative activities, active conservation, ethical and frugal use of resources, a 'right livelihood' (working for useful and beneficial systems)."[3]

2. CARE OF PEOPLE[4] directs us to strive to meet our basic needs for air, water, food, shelter, education, fulfilling employment, and amiable human contact in ways that do not hamper or prevent others from doing the same. We do not exp or disregard others for our own gain. Nor do we destroy the environment that supports us all. Instead, we sustain a basic quality of life that improves our environment while enabling others to do the same.

3. REINVESTMENT OF SURPLUS TIME, MONEY, AND ENERGY[5] to achi the aims of people and earth care encourages us to extend our influence and surplus energies to help others attain the ethics in their own life and work. This helps us all because it strengthens the greater communities in which we all live.

These principles and the ethics are the core of successful water harvesting. They apply equally to the conceptualization, design, and implementation of all water-harvesting landscapes. You must integrate *all* the principles and ethics—not just your favorites—to realize a site's full potential. Used together, they greatly enhance success, dramatically reduce mistakes, and enable you to adapt and integrate a range of strategies to meet site needs. While the principles and ethics remain constant, the strategies you use to achieve them will vary with each unique site.

For a thorough introductory description of water-harvesting principles and ethics and to read Mr. Phiri's full story, see Volume 1, chapter 1 of *Rainwater Harvesting for Drylands and Beyond, 3rd Edition* (Rainsource Press, 2019).

WHO THIS BOOK IS FOR

This volume (the second of a 3-volume set) guides you to harvest water in earthworks in a safe, productive, sustainable way in new and existing landscapes. You will learn how to harvest rainwater, stormwater runoff, and greywater within landscape and garden soil using simple earthworks. Earthworks are simple earthen structures that help reduce outdoor water consumption, decrease water bills, control erosion, enhance soil fertility, grow living air conditioners, support regenerative local resource production, and create a system that gets better with

time as it helps enrich the larger ecosystem. Earthworks help you achieve maximum effectiveness for the least effort and cost while adapting strategies to your site, whether it's urban, suburban, or rural, big or small.

You can choose the best combination of earthworks and variations described here to address the unique conditions of your site, and you can develop new strategies based on what you learn. This book tells and shows you *how to do it* and provides inspiring case studies to teach you and motivate you so you *will do it*. The descriptions are detailed and well-illustrated, so they're easy to follow, and will be useful to backyard gardeners, do-it-yourself and professional landscapers, landscape architects, planners, designers, students, farmers, ranchers, engineers, teachers, community activists, and others.

Dryland-appropriate strategies are emphasized because that's where the need is greatest (see box P.1). Many strategies are based on indigenous traditions that allowed people to survive and thrive in drylands for thousands of years. Yet water-harvesting principles and many of this book's strategies are universally applicable —both wet and dry climates experience drought and flooding. Rainwater harvesting reduces the impacts of dry seasons, droughts, and floods, buffering our lands from changing climates and climatic extremes by making the land more resilient.

Box P.1. Drylands: A Definition

Drylands are typically defined as areas of the world where potential average yearly moisture loss (evapotranspiration) exceeds average yearly moisture gain (precipitation). Evapotranspiration is the combined measurement of water loss to evaporation and transpiration.[6] Transpiration is the loss of moisture from plants to the air via the stomata within their leaves.

More than 16 billion acres (6 billion ha), 47.2% of the Earth's land surface, is dryland. A fifth of the world's population lives in dryland habitat.[7] Normal dry seasons can last six months or more. Droughts can last for years.

Industrial and conventional agricultural sectors consume and contaminate the bulk of our fresh water resources.[8] In contrast, this book focuses on intensive, small-scale strategies ideal for homes, neighborhoods and communities in urban, suburban, and rural settings. We begin work at the top of our "watershed of influence" where we can more easily influence what happens and directly observe and benefit from the results. This makes it easier to implement and maintain the strategies and to more quickly realize their potential. It also leads to less

dependence on consumptive industry and agriculture. As you gain experience and success you will become an example, and your watershed of influence will naturally grow. You begin to plant *seeds of abundance*—rather than scarcity—well beyond your site.

HOW TO USE THIS BOOK AND VOLUMES 1 AND 3

The three volumes of *Rainwater Harvesting for Drylands and Beyond* create a series on how to conceptualize, design, and implement integrated and sustainable rainwater-harvesting systems. I strongly recommend everyone read Volume 1 to get a detailed understanding of water harvesting principles and ethics in the context of integrated sustainable design. Volume 1 puts all three volumes in context. It shows you how to assess your site so you can conceptualize and design truly efficient and productive *integrated* systems that do far more than harvest rainwater. Volumes 2 and 3 describe the specific techniques you need to undertake the general strategies presented in Volume 1. Volume 2 focuses on earthwork techniques that passively harvest rainwater and greywater within the landscape. Volume 3 will focus on roof catchment and cistern systems.

Real-Life stories of people creating, implementing, maintaining, and living with water-harvesting landscapes and systems frame all three volumes. The scale and context varies, but they all illustrate principles in action. You can adapt these ideas to the scale and context your site requires.

VOLUME 2: WATER-HARVESTING EARTHWORKS

The *Introduction* to this volume defines earthworks, explains why you should use them, and shares an inspiring story of how water harvesting brought abundance to a once-dying community.

Chapter 1 is a quick reference guide providing tips on assessing a site's water flow and slope. A comprehensive table summarizes and compares all the earthwork strategies described in later chapters. Use this table to find the right earthworks for your needs, then jump to the appropriate chapters to learn more. Be sure to read the important cautions contained in this chapter. Go on to

further tips on earthwork placement and selection including information on bountifully efficient oasis zones and how to live within your site's water budget.

Chapters 2 through 11 address individual earthwork strategies, defining them, and outlining where to use them and how to implement and maintain them. Tips and examples help you integrate these earthworks into your site so they do more than harvest water. All of these chapters end with stories illustrating how real people in real places have used these techniques—so if you love stories go to the end of each chapter first!

Chapter 12 illustrates how to integrate greywater harvesting within rainwater-harvesting earthworks to keep the landscape thriving in dry seasons and turn "wastewater" into a resource.

The *Epilogue* ties together what you have learned, and gives you a parting vision.

Separate appendices at the end of this book provide specific information about simple tools for measuring slope and placing earthworks, calculations for sizing earthworks and estimating building material volumes, a recently simplified and legal kitchen sink drain-water-harvesting system, and additional resources for water harvesting and permaculture.

Uplifting case studies illustrate how people have transformed their sites using specific water-harvesting strategies and combinations/hybrids of techniques and how you can do likewise.

EVOLUTIONS AND ENHANCEMENTS IN THIS SECOND EDITION

Researching, writing, and massively revising this second edition has reenlivened my water harvesting passion, practice, learning, and inspiration and increased my admiration even more for its many diverse practitioners. These practitioners helped me evolve my abilities and understanding, resulting in significant improvements to this new edition. In a virtuous cycle, publication of the first edition allowed me to travel the world, meeting many of these practitioners and cross-pollinating ideas and strategies as I taught and learned from others. But you don't need to write a book or travel the world to accomplish this, just start where you are.

Along with many other people, I started harvesting water in my own back yard. We learned first hand from our successes and our mistakes—which we figured out and fixed. This prepared us to expand into new contexts when we saw the

need and opportunity. We evolved and grew even further by seeking out those who pushed aspects of their practices beyond our own.

In my life and in this new edition, I focus on seeking out and developing unique ways to collaborate with the natural, living systems that shape and enable the thriving life on this planet to help maximize natural growth and potential. This book aims to help you collaborate with living systems as well. To that end, I've reduced and removed more intensive strategies that are less collaborative with life and more dependent on imported materials (for example, wire-wrapped gabions) and replaced them with more nuanced, synergistic, and easier to build strategies that use on-site materials (for example, one-rock dams that allow vegetation to grow through them to anchor and expand the structures, see chapter 10).

To enable you to see in a new way, over 500 photographs and illustrations are now in color, half of which are new or significantly revised. In addition, dynamic new strategies and stories illustrate natural collaboration, including…

- Irrigating thriving landscapes at residential sites with rainwater- and greywater-harvesting earthworks that double as on-site stormwater controls (chapters 2 and 9)
- Dramatically increasing dry-farming yields using indigenous innovations that "plant the rain" in Syria, Burkina Faso, Niger, Ethiopia, Zimbabwe, Mexico (chapters 3, 4, 6)
- Turning "wastes" into resources including forming broken sidewalk rubble into artistic water-harvesting terrace walls and porous pavement (chapters 4 and 8)
- Bringing back grasslands with the hoofs of intensively herded animals and the fertility of their dung and urine (chapter 6)
- Planting junk mail to hydrate the soil and revegetate the land (chapter 7)
- Changing policy, building codes, and building practice to enable more effective, less-costly systems that rejuvinate local ecologies and economies rather than draining them (chapters 8 and 12 and appendix 3)
- Reviving pasturelands and urban neighborhoods by harvesting runoff from dirt roads and paved streets to create vibrant water-absorbing greenbelts, reduce road maintenance, and counteract the urban heat-island effect (chapters 8 and 9)
- Harvesting liquid water using frozen water by shaping snow berms to harvest snow melt (chapter 9)

• Daylighting once buried creeks and rivers to create local and international destinations of renewal and celebration (chapter 9)
• Regenerating lost wetlands, surface water flows, and groundwater tables with simple water-spreading strategies (chapters 9 and 10)
• Creating innovative designs and installations in which water flow and soil life do the bulk of the work for you by using new principles based on natural patterns of water and sediment flow, soil life, and human behavior (chapters 10 and 12)

DECIDING HOW BEST TO HARVEST YOUR WATER

Despite the many advantages of water-harvesting earthworks (box P.2), they may not be the only water-harvesting strategy to meet your site needs. Tanks/cisterns may also be desirable. How you plan to use your harvested water determines how best to harvest your water (box P.3).

Box P.2. Advantages of Rainwater and Its Harvest with Earthworks

- Water flows downhill, so earthworks are ideal for harvesting rainwater *and* all other free on-site waters (street runoff, greywater, AC condensate, evaporate cooler bleed off, etc.)
- Rainwater (and hail, sleet, and snowfall) is delivered to us free of charge, eliminating the need for costly distribution systems
- Rainwater is the highest-quality source of irrigation water
- Rainwater is salt-free and can help flush plant-damaging salts from the root zone in alkali soils
- Rainwater is a natural fertilizer containing sulfur, beneficial microorganisms, mineral nutrients, and nitrogen
- Rainwater harvesting reduces utility bills
- Rainwater harvesting reduces flooding by reducing flow to streets and storm drains
- Rainwater harvesting reduces nonpoint-source pollution of stormwater
- Rainwater harvesting provides a water source when well, surface, or municipal water is contaminated or unreliable
- Water harvesting helps utilities reduce summer peak demands for water and reduces the volume of wastewater that needs to be treated at water treatment plants
- Water harvesting is fun, and it'll get you dancing in the rain!

Box P.3. Comparing Earthworks and Tanks

CHARACTERISTICS	EARTHWORKS THAT *PLANT THE RAIN*	TANKS THAT *TANK THE RAIN*
Water uses	Provide large quantities of high-quality rainwater to garden and landscape	Provide water for drinking, washing, fire control, and supplemental irrigation. Water quality will vary with catchment surface, tank construction, screening, and maintenance. Rainwater has very low hardness.
Water collection areas	Can collect water from roofs, streets, vegetation, bare dirt, greywater drains, air conditioner condensate, etc.	Need a relatively clean collection surface (typically a metal, tiled, or slate roof) located higher than the tank.
Water storage capacity	Very large potential to store water in the soil and vegetation	Storage capacity limited by the size of the tank
Cost	Inexpensive to construct and maintain. Can build with hand tools, though earthmoving equipment can speed up the process.	Much more expensive than earthworks to construct and maintain. Cost varies with size, construction material, above- or below-ground placement, self-built or prefab, etc.
Location	Do not locate within 10 feet (3 m) of wall or building foundation. May be difficult to use in very small yards with adjacent large roofs.	Can locate within 10 feet (3 m) of wall or building foundation, but you should be able to walk around entire tank to check for, and repair, leaks. Tanks increase water-storage potential in very small yards.
Time period water is available	Water available for limited to extended periods after rainfall depending on soil type, mulch, climate, and plant uptake	Water available for extended periods after rainfall depending on catchment and tank size plus water use
Maintenance	Earthworks work passively; require some maintenance after large rainfalls	Maintenance required, must turn valve to access water and may need pump to deliver water
Erosion control	Very effective for erosion control	Can assist with erosion control
Greywater collection	Very effective at harvesting greywater from household drains	Not appropriate to harvest greywater in tanks due to water-quality issues. Never store greywater in a rainwater tank.
Water quality impacts to environment	Pollutants in greywater and street runoff intercepted & bioremediated in the living soil stay out of regional waterways	Less impact than earthworks to the broad environment
Impacts on urban infrastructure and flooding	Can capture large volumes of water, reducing need for municipal water, storm-water drains, and stormwater treatment, and decreasing flooding	Can capture low to moderate volumes of water, reducing demand for municipal water, stormwater drains, and stormwater treatment, and decreasing flooding
Groundwater recharge	Can directly recharge shallow groundwater or indirectly recharge groundwater by reducing or eliminating need for its extraction	Can help indirectly recharge groundwater by reducing need for its extraction

LANDSCAPE OR GARDEN USE

If you plan to use harvested water (including rainwater, runoff, *and* greywater) for landscape or garden use, begin harvesting water in the soil using *earthworks*. Landscapes that harvest water in soil and are planted with low-water-use native

perennials can typically subsist on rainfall alone once vegetation is established. However, storing water in cisterns gives you the option of applying supplementary irrigation in dry times, especially if a vegetable garden or less hardy non-native vegetation is planned.

POTABLE USE AND WASHING

If you plan to harvest water for potable use and washing, harvest rainwater in tanks, but do not forget the soil. (See Volume 1 for overall guidance, and Volume 3 for specific cistern information.) Direct overflow from the tank, greywater from your house, and runoff from the general landscape into water-harvesting earthworks. The more water you can effectively harvest and hold in the soil, the less supplemental cistern irrigation will be needed.

MATCH THE QUALITY OF WATER BEING HARVESTED TO THE STRATEGY USED TO HARVEST IT

Runoff from clean roofs constructed of metal, slate, or tile, or coated with elastomeric paints approved for rainwater collection systems, is the cleanest and most appropriate water to store in cisterns for domestic consumption and watering vegetable gardens. This runoff can also be harvested directly within earthworks. Stormwater from dirtier surfaces such as earthen slopes, streets, or sidewalks should be directed not to tanks, but to trees and shrubs in earthworks. Household greywater should be directed to and utilized within mulched basins planted with trees and shrubs. Do not store greywater in tanks. Instead, direct greywater directly to mulched and vegetated earthworks.

Keep in mind the question, “How do I plan to use my harvested water?” as you read the comparisons of these water-harvesting approaches in box P.3.

If water-harvesting with earthworks is appropriate for your site and needs, read on; the rest of this book shows you how.

Introduction Earthworks Defined, Their Advantages, and a Story of Success

Just as water is the foundation of life it must also be the foundation of design of the built environment.

—Betsy Damon, Founder of Keepers of the Waters

WHAT IS RAINWATER HARVESTING WITH EARTHWORKS?

The next time it rains, run outside and cup your hands to capture the water falling freely from the sky. Drink it and taste the sweetness. Share it. fig. I.1).

Fig. I.1. Rain-fed bounty

Grab a shovel to make cup-like shapes in the soil, so plant roots, earthworms, fungi, and myriad other life forms can also drink the sweetness. These grow and share the bounty of food, oxygen, shelter, fertility, medicine, building materials, wildlife habitat, and beauty. This is rainwater harvesting with earthworks.

Water-harvesting earthworks or "rain gardens" are the simple strategies and landforms that capture and "plant" rain and localized runoff, our *highest-quality* sources of irrigation water,[1] which come to us *free of charge*.

Earthworks function as easy and convenient *passive*-irrigation and erosion-control systems. There are no manufactured tanks, no mechanical pumps, and no plumbed irrigation systems with associated maintenance requirements, though such systems can be used in conjunction with earthworks. Earthworks store water in the soil—our largest and least expensive "tank"—with the force of gravity and the living pumps of plants moving water through the system. Earthworks function whenever rain falls and water flows, whether you are there or not. Water-harvesting tanks and mechanical irrigation setups are *active* systems that require you or your valve and timer system (ultimately you) to turn the water on and off. Mechanical irrigation systems require regular maintenance and are prone to wasteful leaks. While earthworks take effort to install, over time they typically cost less and require less maintenance than active systems.

Earthworks are appropriate for use in landscapes, gardens, farms, ranches, parks, schoolyards, street medians, public rights-of-way, restoration sites, and lots of other places. Their specific shapes are based on the unique topography and needs of each site. From bowl-like depressions in flat soil, to serpentine contour berms cutting across slopes, to courses of rocks laid across the bottom of an ephemeral drainage, they all act as nets, slowing, capturing, and infiltrating water into the soil and healing erosion at the same time.

Earthworks *hydrate* rather than dehydrate the land. They can cost as little as the price of a shovel or as much as the cost to utilize an operator and large earth-moving equipment. They *maximize the potential* of available rainfall, concentrating it to create thriving landscapes that slash water bills, reduce use of nonrenewable water supplies (such as depleting groundwater), decrease downslope flooding, and improve water quality.

Compare a landscape that drains rainwater and other resources (figs. I.2A, I.3A,B) to a landscape that harvests rainwater and other resources (figs. I.2B, I.3C).

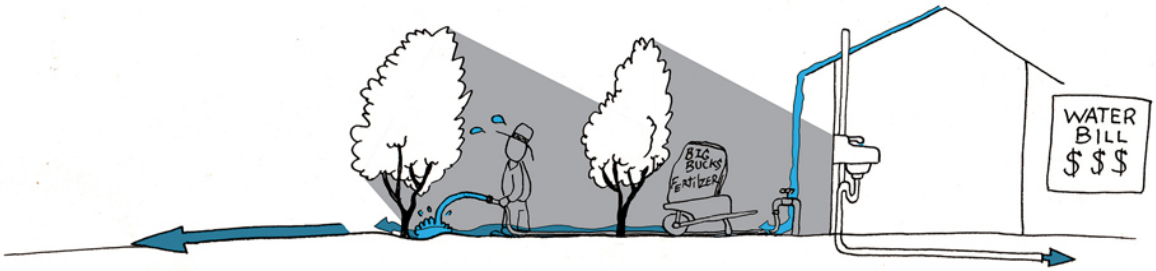


Fig. I.2A. A landscape actively wasting and consuming resources. Rainwater, greywater, and organic matter are drained away. Homeowner must purchase/import resources to replace those lost. Arrows denote stormwater runoff and sink-drain-greywater flow.

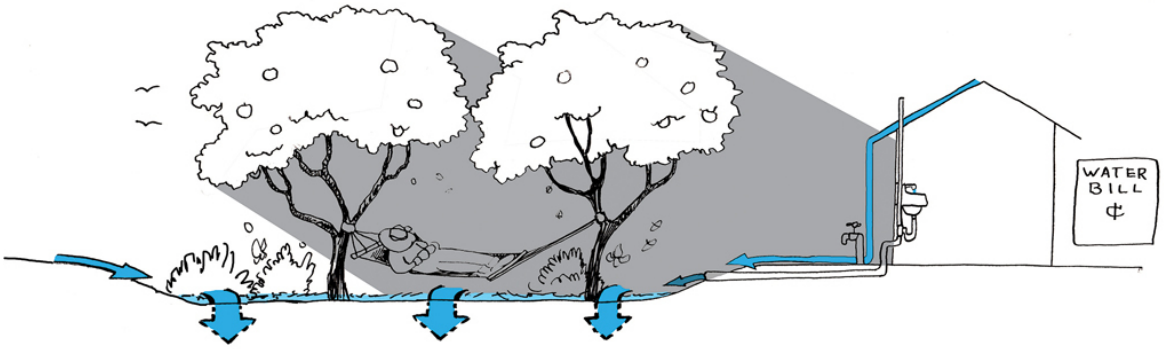


Fig. I.2B. A landscape passively harvesting resources. Rainwater, greywater, and organic matter are freely harvested in the soil to naturally grow more on-site resources. Arrows denote stormwater runoff and sink-drain-greywater flow.

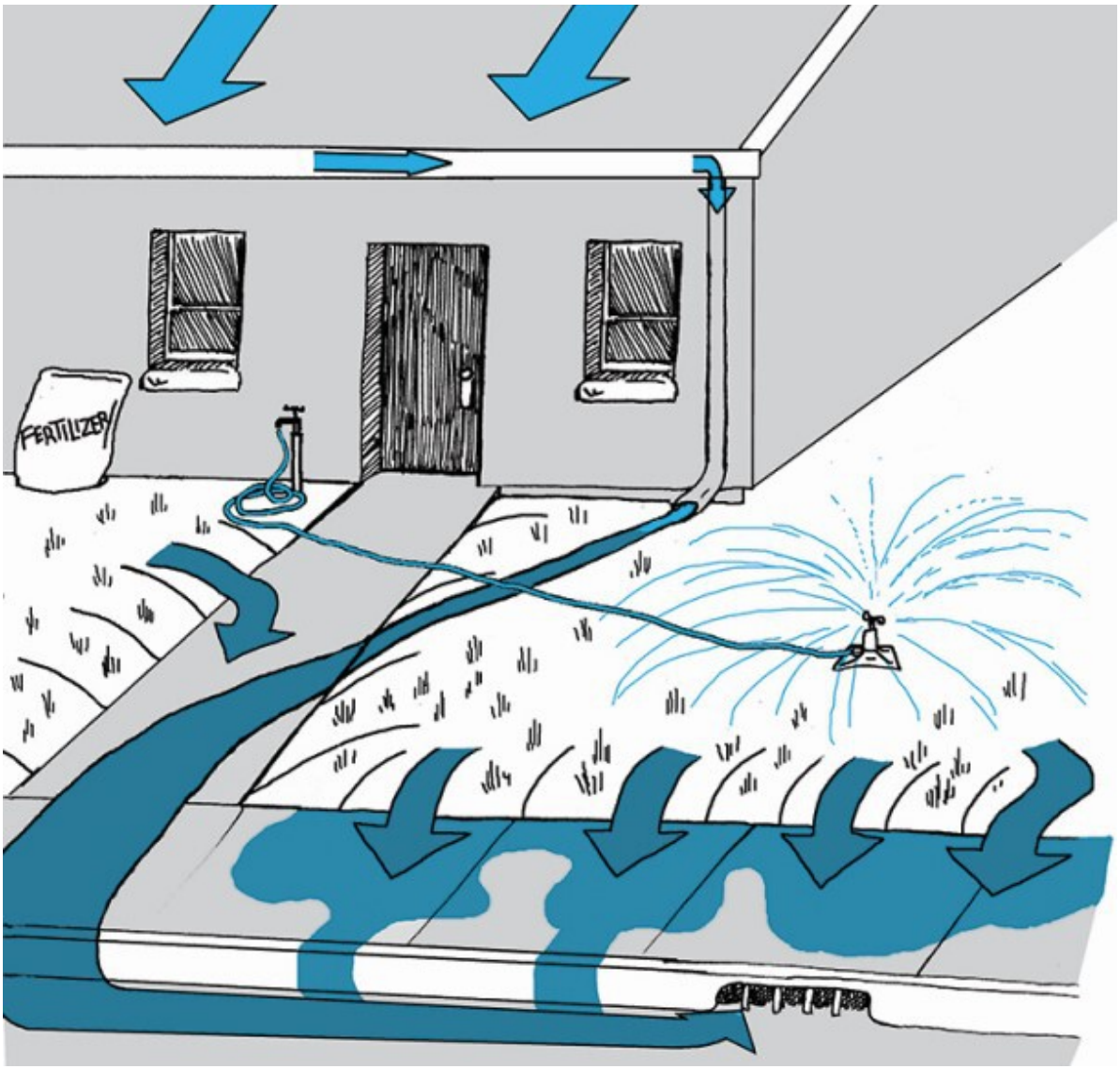


Fig. I.3A. A *draining*, water-consumptive, convex landscape of turf grass that is dependent on sprinkler irrigation with imported drinking water.

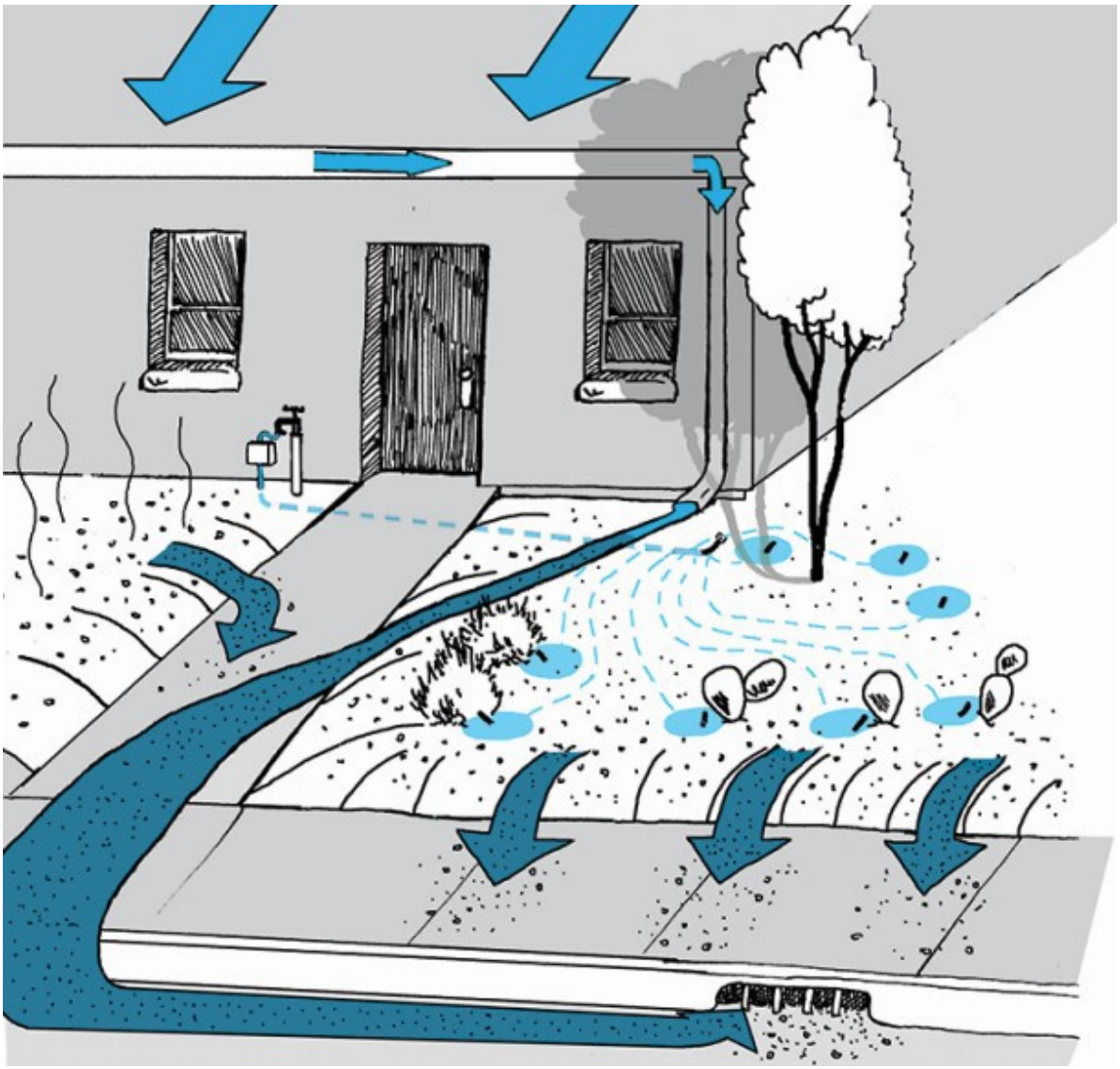


Fig. I.3B. A *draining* convex landscape of gravel and lower water-use plants promoted as "water-*conserving*" despite still being heavily dependent on imported drinking water for drip irrigation, while still draining the majority of free on-site waters away.

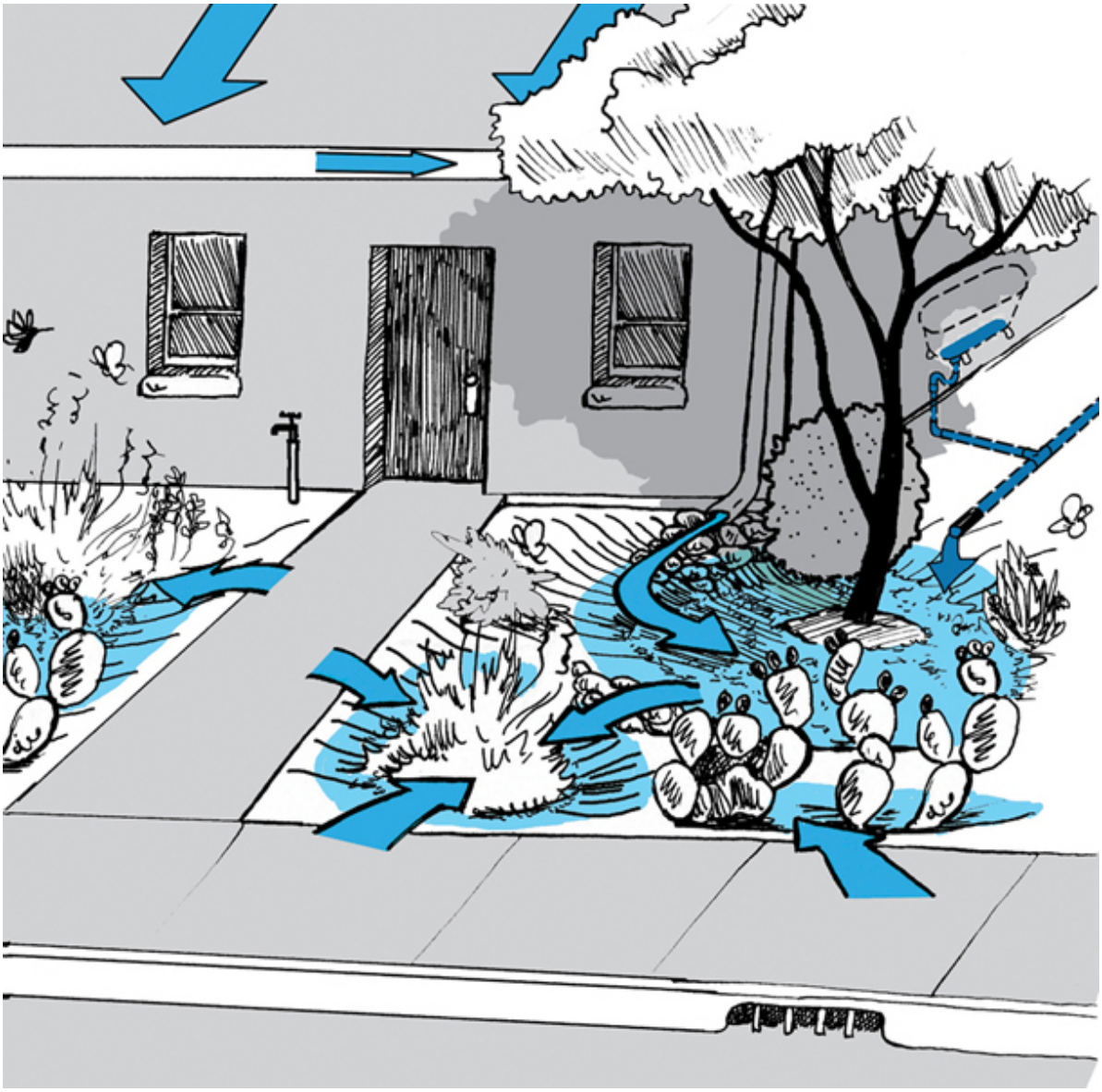


Fig. I.3C. A *harvesting* concave landscape that is mulched using organic matter and planted with native vegetation is water-*restoring*. Once established, it can thrive solely on captured rainwater and runoff—no imported irrigation water is needed—though greywater harvesting boosts performance still further.

A DRAINING LANDSCAPE

A draining landscape drains and dehydrates the land.

In a draining landscape, plants sit on top of a convex landform that drains away water, topsoil, and organic matter, stunting plant growth and increasing water consumption over the long term. Roof runoff is directed past plants into streets and storm drains via gutters, downspouts, and landscaped "stream beds." This ejected water can be a liability, flooding streets and other areas downstream.

Hardscapes (sidewalks, driveways, and patios) slope away from the landscape into streets and storm drains, adding to flooding problems (figs. I.3A,B).

Resulting water loss: if 12 inches (305 mm) of rain fall on this parched site in a year, as little as 4 inches (100 mm) may actually infiltrate the soil, while 8 inches flow away as runoff, *depleting the benefits of the already sparse rainfall*. Adding to the madness, automatic irrigation systems in these landscapes frequently turn on just hours after a downpour or even while rain is pouring from the sky.

This waste leads to scarcity.

A HARVESTING LANDSCAPE

A harvesting landscape collects and generates multiple resources while hydrating the land.

In a harvesting landscape, climate-appropriate plants are placed within or beside mulched, concave earthworks that function like *living sponges*, retaining water, topsoil, and organic matter. This landscape enhances rather than depletes local resources.

Earthworks direct roof runoff to the soil, where this resource infiltrates to the root zone of plants. Hardscape that is raised and sloped so it directs runoff into the landscape further enhances on-site water resources, while reducing street flooding, sediment loss downslope, and the risk of slipping on ice-covered hardscape in cold climates (fig. I.3C).

Resulting water gain: if 12 inches (305 mm) of rain fall on this water-harvesting landscape in a year, and the roof area and sidewalk area are each equal to the landscape area, then 12 inches of rain falls directly on this spongy landscape, another 12 inches run off the roof to the landscape, and an additional 12 inches run off the sidewalks to the landscape, *tripling available rainfall* to a total of 36 inches (914 mm) per year!

Once plants are established, using this harvested water will offset or even eliminate the need to irrigate with potable municipal water or well water, especially low-water-use native plants. Flooding is averted because overflow is routed and managed as a resource (the fifth water-harvesting principle). So, while earthworks may take more work to build in the short run, there is far less work, cost, and maintenance in the long run. A harvesting landscape mimics natural systems in which life thrives where water lingers.

This stewardship of the landscape and water leads to abundance.

AIM HIGHER BY AIMING FOR ABUNDANCE FOR ALL

What if we aim not just to minimize or solve a *problem*, but to maximize the potential good by enhancing as yet unrealized *potential*?

If we aim only to solve a *problem* we'll unconsciously put a ceiling on what's possible, because once we think we've solved the problem we stop. But if instead we aim to find, tap, and enhance as yet unrealized *potential* there is no ceiling. As we learn to see and to collaborate with potential, we naturally strive for still more potential as our understanding and practices evolve.

For example, with a minor shift in approach there is huge potential to increase the benefits of a common water conservation program—*cash for grass* turf removal rebates, which strive to *minimize* the problem of using excessive potable water to irrigate lawns. The rebates pay for the conversion of fig. I.3A-like landscapes to those like fig. I.3B in order to reduce irrigation demand: problem seemingly solved. But these conversions miss the bigger potential to fix the hydro-logic dysfunction of the draining topography of the landscapes, which is causing dehydration of the landscape and flooding of neighborhoods. New problems arise as sun-baked gravel increases temperatures and the cost of cooling adjoining homes, gravel and sediment washes away—impeding walkways and streets and clogging storm drains, and the mining and transport of that gravel and rock degrades our environment.

What if we looked instead at how to solve the problem and we simultaneously leveraged as yet untapped potential by asking:

What free untapped water resources are already on site that could be used instead of potable water for irrigation? How can every on-site "waste" become a resource? What if gravity was our primary distribution system? How could the beautiful, well-adapted, multi-use plant palette indigenous to the area be used instead, since it survives without any human inputs or supplementary irrigation? Which of these native plants could provide on-site food, medicine, craft material, nitrogen-fixation, and/or fragrance? How can we work with other on-site life forms (such as soil microorganisms) to enhance fertility, water availability, plant health, and carbon sequestration? What if, rather than just conserving resources, we strove to enhance and multiply resources at no additional expense for the benefit of all?

Asking these inviting questions about potential can lead us to much more effective harvesting practices and programs whose common sense changes to the landscape restore hydrologic function, hydrate the landscape, control flooding,

enhance fertility, grow beautiful sheltering vegetation, and manifest additional potential. Using non-potable waters like storm-water runoff and greywater for passive gravity-fed irrigation can be incentivized. Cultural knowledge on the many traditional and evolving uses of native plants can be researched and celebrated in landscape plant selection. Organic matter that feeds and shelters soil life can be used as groundcover in place of imported gravel. All this *potential* and more can be realized while addressing the need to dramatically reduce potable water consumption for irrigating lawns (fig. I.3C). See box 1.1 in chapter 1 for characteristics of regenerative systems that can further elevate your practices, programs, and potential.

Box I.1. The Abundance of Rainwater

One inch of rain equals 0.623 gallons per square foot of catchment surface.

One inch of rain falling on a 1,000-square-foot catchment surface equals 623 gallons of water.

One inch of rain falling on 1 acre of catchment surface equals 27,154 gallons of water.

Ten millimeters of rain falling on 100 square meters of catchment surface equals 1,000 liters of water.

Ten millimeters of rain falling on one hectare of catchment surface equals 100,000 liters of water.

EARTHWORKS – A RESURGING ANCIENT STRATEGY

Before the advent of modern irrigation and pumping technology, people used a diverse array of water-harvesting and water-conserving earthworks in all populated dryland environments and many wetter climates to recharge wells, grow food and other vegetative resources, and control flooding and erosion.[2,3,4] As Fred Pearce states in *When the Rivers Run Dry*, "Harvesting the rain was once a worldwide technology on which millions of people depended. Every locality had its own system. Almost everyone did it."[5] Water- and soil-harvesting terraced fields and other earthworks have been used throughout wet and dry areas of Asia, North and South America, Africa, and Europe for generations (see Volume 1, appendix 2 for traditional Native American techniques in the U.S.). There is a 4,000-year-old tradition of harvesting water in soils of the Indian subcontinent.[6]

For centuries past, and again in the present, earthworks allow dry-farmed production of pomegranates, almonds, figs, peaches, carob, and grapes in the

Negev desert of Israel on just 4 inches (100 mm) of annual rainfall.[7] Use of earthwork strategies likely spreads quickly because they are effective and can readily be made with materials on hand such as soil, rock, and plants. Dryfarmed fields that harvest rain typically have yields 2 to 7 times higher than those that do not.[8]

When mechanical pumps, piped water, and large-scale dams and river-diverting canal systems were introduced from the early 1900s on, the use of earthworks went into decline. Piping in water from elsewhere was perceived to be more convenient than using water harvested on site. The availability of water no longer seemed to depend on rains and rainfall harvesting. We grew accustomed to water coming from pipes, canals, sprinklers, and irrigation tubing rather than the sky. But now the pipes, canals, sprinklers, and tubes are starting to run dry.

Across the globe, we are extracting water from rivers and aquifers more rapidly than natural recharge replenishes it, causing groundwater levels to drop and flows in the majority of our rivers to dwindle.[9] In addition, much of this water has been contaminated by agricultural, industrial, urban, and suburban non-point-source pollution (contaminants collected and carried within our unchecked or unharvested runoff).

The water scarcity we have created is now bringing about a resurgence of interest in water harvesting. These techniques efficiently use the water we have, reduce the water we extract, and can enhance recharge of aquifers and river flows by putting more rain in the soil than we take out. Around the world more and more individuals, groups, and communities are again harvesting the rain. The result is more verdant landscapes, rising well levels, new springs, and even the revival of once-dead rivers. The more people who do it, the greater the effect. You will read about such successes at the end of each chapter in this book.

"If you quench Mother Earth's thirst, she will quench yours."

—Pandurang Shastri Athavale, Vedic scholar and water-harvesting advocate, *When the Rivers Run Dry*

EARTHWORKS PLANT THE RAIN TO TURN WATER SCARCITY INTO WATER ABUNDANCE

All the earthworks presented in this book harvest and plant the rain in the earth and vegetation, so the water moves slowly and productively through the soil of the watershed, rather than quickly and erosively running over and off the soil's surface. The earthworks described here do not store water on top of the soil like a puddle or a pond where water would be lost to evaporation or mosquitoes could breed. Since mosquitoes need at least three days of standing water to evolve from eggs to adults,[10] properly constructed water-harvesting earthworks never have standing water for more than 12 hours and typically not more than one hour. Earthworks should be porous sponges that quickly pull water beneath the surface. Pervious surface mulches of organic material such as leaf drop, woodchips, bark, straw and/or compost are key to creating this sponge. Vegetation is just as important. The plants' roots create thousands of micro-channels throughout the soil, speeding up infiltration of water into the soil and steadily increasing the soil's storage capacity as plant and soil life grows and diversifies.

As "living pumps," vegetation, mycorrhizal fungi, and other soil life access the moisture harvested within the soil and distribute it throughout the plants, enabling you to eat harvested water in the form of a peach, pomegranate, olive, or mesquite pod. Water in the form of shade trees cools you. Water pumped into windbreak trees shelters you. This "tree water" reduces erosion and improves air quality. You enjoy the water in the form of flowers and the hummingbirds and butterflies they attract. With rain-irrigated plants you sustainably grow and produce resources, rather than wastefully buy and consume resources (fig. I.4).

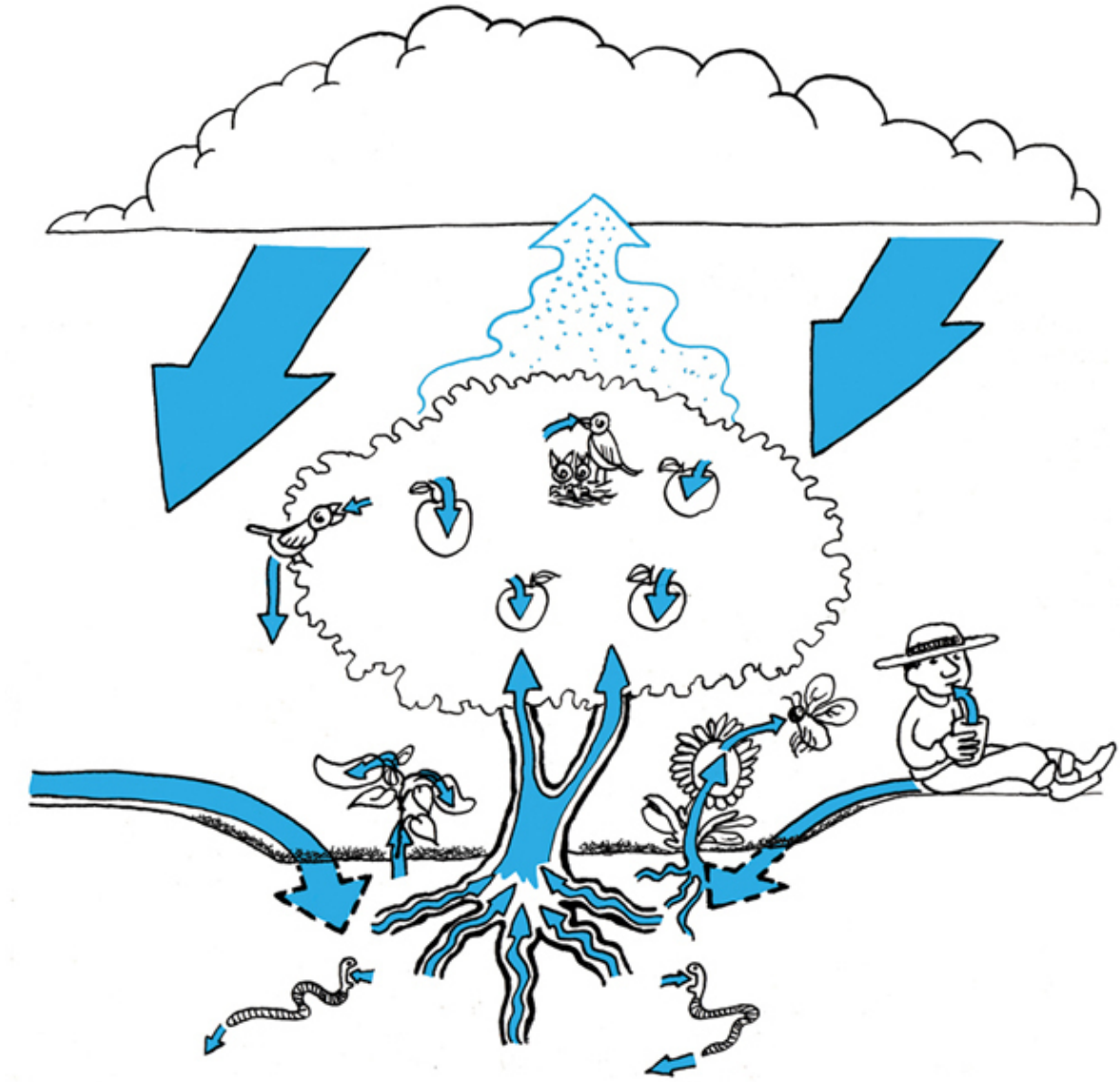


Fig. I.4. A living sponge and living pump of organic matter, healthy soil, and diverse vegetation quickly infiltrating water then pumping it back out in the form of fruit, shade, fertility, erosion control, wood, beauty, and wildlife

In many (but not all) hydrologic environments, rain and snow harvested in soil can make their way to springs, creeks, rivers, and wells. Surface runoff can supply quick, high-volume infusions of water (sometimes in the form of destructive floods), but the slow subsurface path water takes from soil to springs, creeks, rivers and wells provides more consistent and productive flows throughout the year, including dry times. The more water harvested in wet seasons, the more water there is to feed the springs, creeks, rivers, and wells that yield water throughout the year.

EARTHWORKS ARE THE *FOUNDATIONAL STRATEGY* OF SUSTAINABLE LANDSCAPES

Earthworks, not drip-irrigation systems, are the foundational strategy of water-conserving, sustainable landscapes, because earthworks that harvest direct rainfall can also harvest greywater, air-conditioning condensate, runoff, rainwater distributed from cisterns, and municipal water used in the landscape. No matter what type of water is harvested, earthworks reduce erosion, decrease downstream flooding, enhance stormwater quality, and retain organic matter falling from plants, which increases soil fertility. Drip-irrigation systems harvest nothing. Their only purpose is to distribute pressurized water (usually pumped in from off site) via plastic pipe and drip emitters to individual plants.

Yet drip-irrigation systems are promoted as the pinnacle strategy for achieving water-efficient landscape. Studies prove otherwise: While drip irrigation can be more efficient than flood or sprinkler irrigation of agricultural monocultures, diversely planted drip-irrigated landscapes, and gardens often use more water than those without drip systems (see box I.2).

Box I.2. Manual Awareness Saves More Water Than Automatic Convenience

According to a report by the American Water Works Foundation:

- Households that employ an automatic timer to control their irrigation systems use 47% more water outdoors than those that do not. This is because timer settings often are neither changed with seasons nor once plants are established, so automated systems irrigate whether plants needed water or not, and even if it is raining. In addition, leaks ar seldom noticed or repaired.
- Households with drip-irrigation systems use 16% more water outdoors than those withou drip-irrigation systems. Landscapes and gardens typically have a diverse array of plants wi differing water needs, yet all plants on a drip system are watered, even if only a few plant actually need the water.
- Households who water with a *hand-held* hose use 33% less water outdoors than other households.[11] You won't water any more than you have to, because there are other thin you'd rather be doing. Note: For this to work, you must hold the hose when watering. Leaving the hose running on a plant unattended does not conserve water.

Earthworks reduce or eliminate our need to apply supplemental irrigation whether via drip irrigation, hand-held hose, or other means. Using earthworks, we can achieve a more sustainable hierarchy in household and community water management in which:

- Rainwater and localized runoff, our on-site water resources, are the *primary* wat source for our landscapes and gardens.

- Greywater is the *secondary* water source for our landscapes. Greywater is househ "wastewater" that drains from sinks, clothes washers, showers, bathtubs, reverse osmosis water filters, and the condensate from air conditioners.

- Municipal water or groundwater from private wells is strictly a *supplemental* sou for landscapes used *only* in times of need such as drought. This is water pumpec onto, or pumped up to, our site.

By embracing this sustainable water-use hierarchy and using a climate-appropriate plant palette, you can sustainably support a lush landscape year round using only harvested rainwater and greywater, even in times of no rain. This spares the use of precious and expensive potable water for irrigation. As a society we spend vast resources purifying water to drinking water standards, as well as building and maintaining pipes and pumps, and using fossil fuels to deliver water throughout the community while keeping it safe to drink. It is a waste of all these resources to cast this potable water into our dirt and toilets.

About 30% of the potable water consumed at single-family residences in the U.S. is used for outdoor irrigation.[12] In hot dry climates potable water consumption for irrigation can be much higher. In Albuquerque, NM 40% of potable water goes to irrigation.[13] In San Diego, California, Denver, Colorado, and Phoenix, Arizona, well over half the drinking water consumed at single-family residences is used for irrigation.[14]

In a typical U.S. household, the flushing of toilets accounts for up to 30% of all indoor potable water use.[15] Most people are not conscious that their commodes are filled with drinking water (which they soil daily), but dogs are. Perhaps that's why they drink from the toilet bowl! Waterless compost toilets are a solution.

The potential of water harvesting is great—even in dry communities. A study found that average rainfall in the average urbanized sections of the desert city of Tucson, Arizona, (12 inches or 305 mm of rain per year) is equivalent to 74% of the total water supplied to those sections by the local water utility.[16] Thus, just by utilizing this rainfall instead of potable water to irrigate landscapes, water consumption could be reduced by 30% to 50%.

ADDITIONAL BENEFITS OF EARTHWORKS

Earthworks create living water-harvesting systems that can improve with time.

Soil—the "earth" of earthworks—is alive. The more vegetation and other life there is within it, the more life it can support, for life builds on life (figs. I.5A, B). As Toby Hemenway explains in *Gaia's Garden*, "An acre of good pasture may support a horse or two, say about a half-ton of aboveground animals. But living in the soil of that acre may be 2 tons of worms and another 2 tons of bacteria, fungi, and soil animals such as millipedes and mites. That one-horseper-acre soil may contain eight or ten horses' worth of animals below ground."[17] That soil life is what makes the horse's life and ours possible.

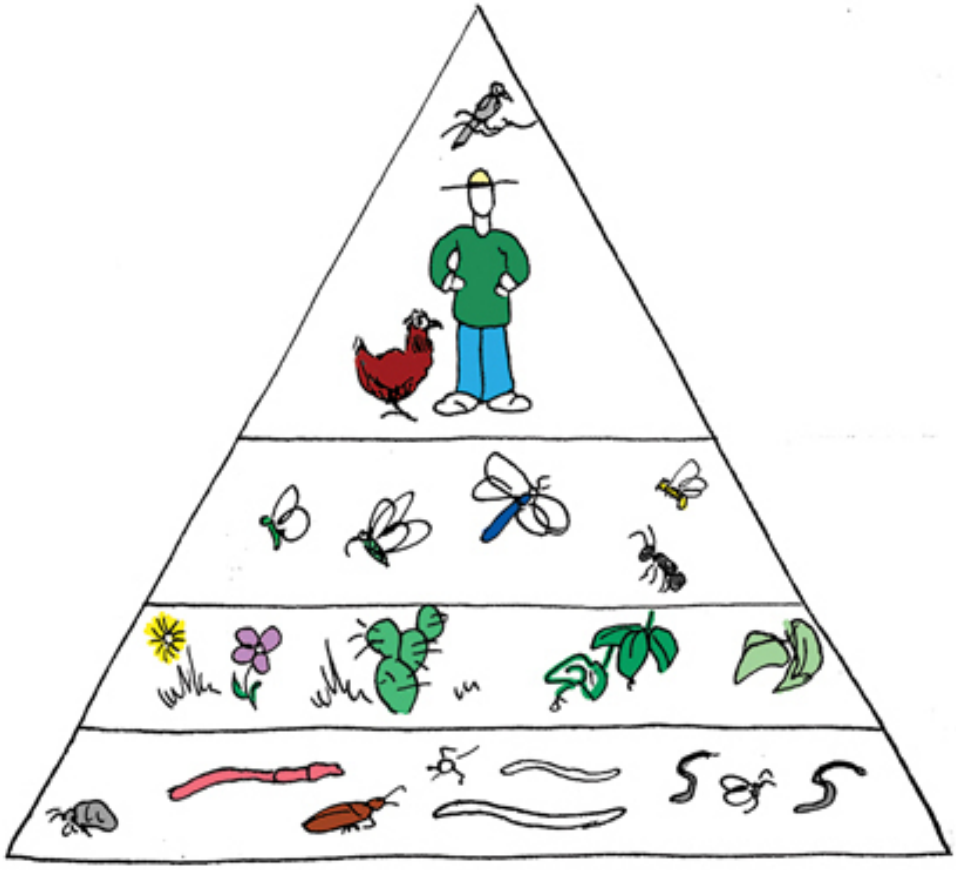


Fig. I.5A. Poor soil supporting a limited amount and diversity of life. Adapted from *Gaia's Garden*, Chelsea Green Publishing, 2009

Fig. I.5B. Healthy and diverse soil life supporting a greater amount and diversity of life and resources. Adapted from *Gaia's Garden*, Chelsea Green Publishing, 2009

Soil animals, plants, fungi, and microorganisms are the ultimate transformers and recyclers converting the solar energy, rocks, animal and insect waste, and dead matter into food, fertility, and other energies. Plant and soil life transforms things we cannot readily use into resources that we can use (fig. I.6). The more healthy soil life that exists, the more resources it can produce. Yet the health of soil and plants depends not just on soil life and nutrients, but the depth and speed of their flows and interconnections.[18] Water lubricates these flows and interconnections. Water carries plant nutrients from the roots upward, and food from the leaves downward, and plays an important role in photosynthesis—the solar-powered production of vegetation. Water also speeds the decomposition process and the

transfer of energy between life forms, while speeding the growth of vegetation, earthworms, and other soil life.

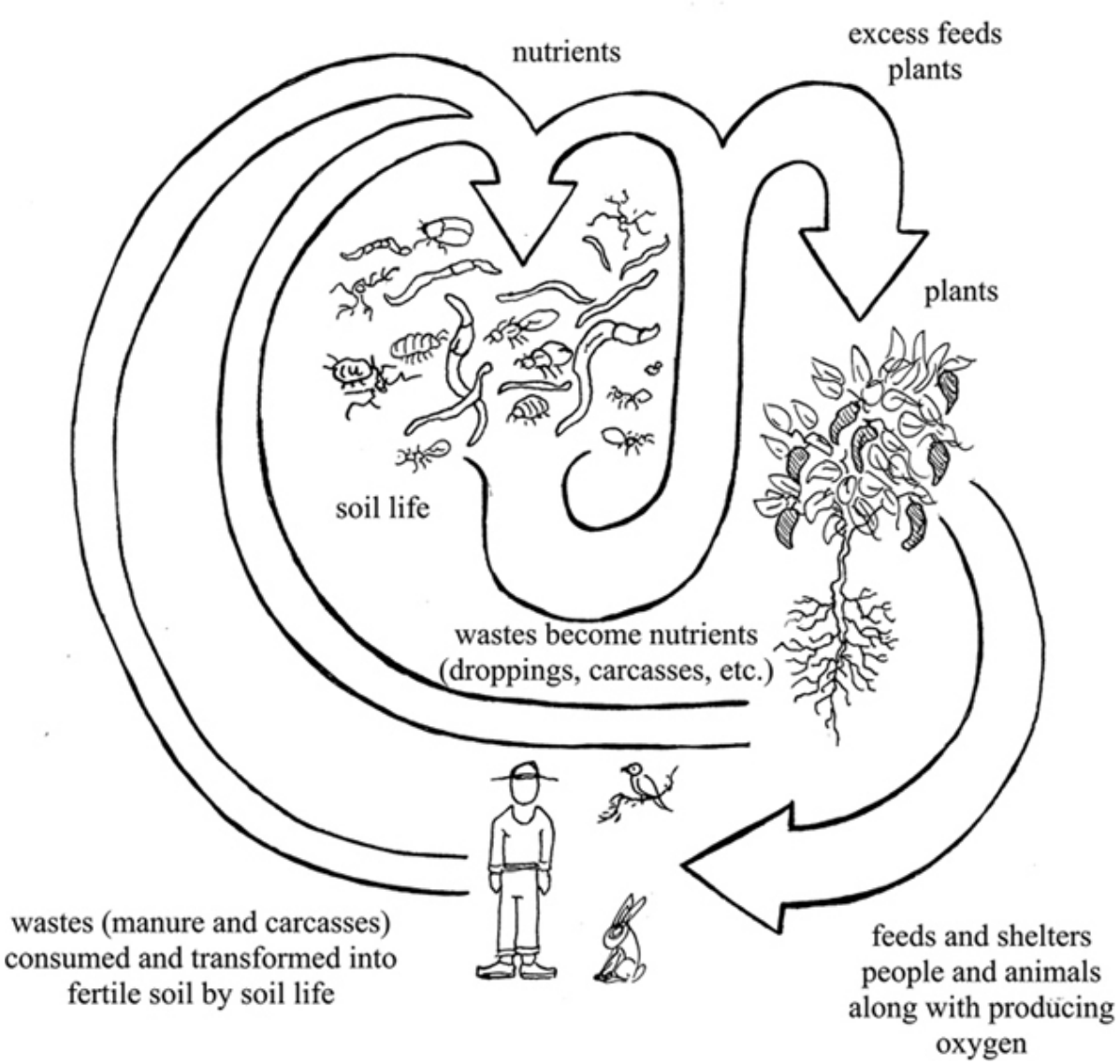

nutrients
excess feeds plants
plants
soil life
wastes become nutrients (droppings, carcasses, etc.)
wastes (manure and carcasses) consumed and transformed into fertile soil by soil life
feeds and shelters people and animals along with producing oxygen

Fig. I.6. Nutrient flows whereby soil life transforms "wastes" and nutrients into more life and resources. Adapted from *Gaia's Garden*, Chelsea Green Publishing, 2009

This life, and the resulting harvest of leaf-drop and humus within the earthworks, then moderates extreme conditions, both dry *and* wet (fig. I.7B). In dry, fast-draining sandy soils, plants, surface mulch, and other organic matter in the soil help absorb and hold onto more water. Toby Hemenway reports that, "soil with as little as 2% organic matter can reduce the irrigation needed by 75% when compared to poor soils with less than 1% organic matter," and "shading soil

[with mulch and plants] has been shown to reduce evaporation loss by over 60%."[19] In wet, poorly draining clayey soils, plants, mulch, and organic matter help increase the soil's porosity, enabling vast amounts of water to be absorbed without losing the soil's ability to hold air, since it is the lack of air that drowns waterlogged plants.[20] Whatever the climate, growing roots, burrowing earthworms, and branching fungi thriving in the sheltered environment of vegetated earthworks continually expand subsurface microchannels through which water can quickly infiltrate and nutrients can rapidly be exchanged; life building on life.

Fig. I.7A. Depleting the living sponge by vacuuming a site's nutrient-rich "waste" of fallen leaves and organic matter. Credit: Jenny Leis

Fig. I.7B. Enhancing the living sponge by recycling nutrients and organic matter. Prunings are cut up and used as mulch, along with fallen leaves, for the plant from which they came. In a healthy system there is no such thing as waste. Compare to fig. I.7A.

LIFE SUPPORTED BY EARTHWORKS MITIGATES CLIMATE CHANGE AND EXTREMES

The availability of more water within and beside water-harvesting earthworks grows more life, which in turn shades, cools, and shelters more of the Earth's surface from intense sun, wind, flooding, and other extremes. There is a powerful, beneficial partnership between the hydrologic cycle circulating life-giving water and the soil-building, carbon-based/carbon-cycling life in the soil—known as the s*oil-carbon sponge*. According to climate scientist and soil microbiologist Walter Jehne, the vast majority of the heat dynamics and hydrologic cooling on Earth is governed by our planet's hydrologic cycle.[21] And that cycle, coupled with the soil-carbon sponge, helps maintain a stable climate on our planet such that the amount of heat released to space is equal to incoming heat from the sun—though our planet has been holding onto more heat than it releases since about 1750 due to human-influenced climate change and the destruction of the soil-carbon sponge.[22]

By understanding the synergy between the hydrologic cycle and the soil-carbon sponge, we can design our sites to beneficially collaborate with these natural processes. Well-vegetated soil absorbs and reradiates less heat to the atmosphere than non-vegetated bare earth. Evapotranspiration of water from this vegetation results in even more cooling because the latent heat/energy needed to change liquid water to water vapor is absorbed from solar radiation without increasing the air temperature. Water vapor rises into the atmosphere and collects around cloud "seeds"—precipitation nuclei—ideally tiny hydroscopic microbes or bacteria that grew in the stomata cavities of plant leaves and then were released into the air (so you could say rain is a microbial symbiotic process).[23] The resulting clouds further shade the earth before the water vapor turns back into liquid rain drops, releasing energy/heat back into space. Rain from the clouds cools and rehydrates the earth's surface, where soil-building, carbon-based life—the soil-carbon sponge—sequesters atmospheric carbon and rapidly infiltrates the water, which in turn supports more plant growth (fig. I.8). And more atmospheric moisture is invited into the area's sky as the rainstorms release atmospheric pressure, creating a moisture-welcoming low-pressure system, rather than a moisture-deflecting high-pressure system.

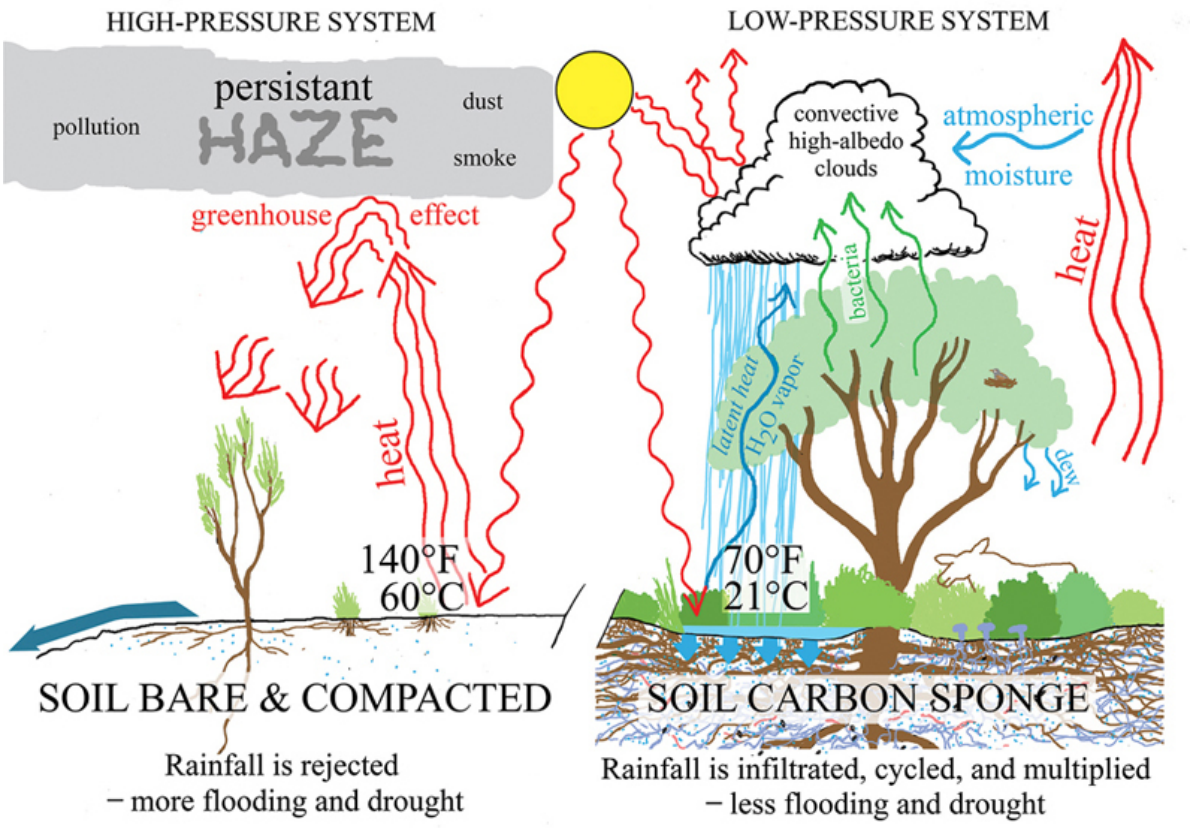


Fig. I.8. The condition of the soil carbon sponge controls the fate of rainfall and affects climate. Adapted from "Recognizing the Soil Sponge" by Peter Donovan, SoilCarbonCoalition.org

The clouds created by the process described above are very different from haze, which is created by water vapor collecting around airborne dust particles, aerosols, and pollutants. Heat reflected off the earth's surface up into the air is reflected back down to the earth's surface by haze—the planet-heating greenhouse effect. Haze does not generate rain, so haze lingers much longer, and unlike clouds, which disperse after a storm enabling rising heat to escape to space (especially felt at night), haze does not disperse, but instead continues to trap heat in the atmosphere.

As Peter Donovan states in his essay "Recognizing the Soil Sponge,"

"Deforestation, fire, and agriculture have tended to move landscapes leftward (fig. I.8)*, baring soil, increasing fine dust particles that nucleate haze but not rain, planting short-season annuals, shortening the length of the green season and the sugary plant root exudates that feed soil porosity and aggregation. Bare soil heats up, radiates,*

and some of this heat is re-radiated back from greenhouse gases. Regular fire or tillage bares soil and prevents the soil carbon sponge from developing. High-pressure domes over large expanses of hot bare ground repel rain. These landscapes multiply heat and aridity.

On the right (fig. I.8), *the formation of high-albedo rain clouds from abundant transpiration with bacterial precipitation nuclei helps recycle water locally, while the pressure drop from large-scale condensation drives the biotic pump, which brings in moist air from the oceans. When the clouds clear, heat can escape. Abundant plants harvest atmospheric moisture as dew* (fig. I.9). *More solar energy is dissipated upwards by transpiration, and less by sensible heat [heat that changes temperature]. These landscapes multiply rainfall and cooling…*

Fig. I.9. Fog-harvesting vegetation. Note the puddles beneath the trees on whose leaves the fog condensed into water drops, which then dropped to the soil and pavement below. Photo credit: Erin O' Neill, SeedsAndStones.blog. Search "Fog Harvesting" at HarvestingRainwater.com for more

…Carbon embodies the solar-powered circle of life, the great biogeochemical carbon cycle powered by photosynthesis and governed by the metabolisms and choices of zillions of self-motivated living organisms, most of them microbes. Though the work of carbon cycling is tiny copared to the work of water cycling, carbon cycling wields enormous leverage with its complex and transformational chemistry, leading to a coupled carbon and water cycling that governs the balance between incoming solar radiation and outgoing longwave radiation. In the soil, the decomposition of living things forms the soil carbon sponge, which can resiliently sustain plant life, affect the earth's hydrology and heat balance, and may give humans the near-term leverage we need to avert catastrophic climate change, restore hydrologic function, maintain our economies and civilizations, and maintain and enhance human health."[24]

EARTHWORKS HELP THE GOOD FLUSH OUT THE BAD

Soil fertility degrades over time on dryland farms and landscapes dependent on imported ground or surface water for irrigation due to the continual buildup of the salts introduced with the imported water (fig. I.10). High-sodium soils crust up or lose their structure, reducing the ability of water and roots to penetrate the soil and the ability of vegetation to take up water and conduct photosynthesis.[25] Such salt accumulation results in the loss of 25 million acres (10 million ha) of farmland around the world every year.[26]

Fig. I.10. Salt buildup at the base of four plants irrigated with municipal water. See the white circular salt deposits around the base of each plant irrigated with drip irrigation emitters. Note how the irrigation emitters, the water they emit, and the salt do not extend much beyond the plant, thus roots are not encouraged to extend further, which would better stabilize and support the plants. Tucson, Arizona.

Yet soils on dryland farms and landscapes irrigated primarily with harvested rainwater steadily increase in fertility and their ability to hold water, because salt-free rain steadily flushes the salts of alkaline soils out of the plant-root zones. Researcher Michael Evenari found that harvesting rain on fields in the Negev desert continually decreased previously severe soil salinity to the point that moderately salt-sensitive crops including apricots, almonds, and carob could be grown.[27]

All of this became dramatically apparent to me during a trip to Rajasthan, India, where I visited farm after farm with salt-crusted soils abandoned after less than 30 years of groundwater and canal irrigation (fig. I.11). I also visited many thriving farms in the same area that had been irrigated with harvested rainwater for generations, and none showed signs of salt buildup in the soil (fig. I.12).

Fig. I.11. This well and the field in background were abandoned after groundwater was depleted and irrigation with pumped groundwater raised salt levels in the soil to the point that plants would no longer grow. Jaisalmer District, Rajasthan, India.

Fig. I.12. This water-harvesting field has been productive for generations without any signs of salt buildup in the soil. A khadin, or large berm at the low end of the field, captures and backs up runoff to the point that it spreads over and infiltrates within the entire field. A winter crop of mustard green seedlings is being grown. Jaisalmer District, Rajasthan, India.

EARTHWORKS CAN CREATE LONG-LIVED, SELF-MAINTAINING OASES

Earthworks always perform better when maintained, though once established, a well-designed and -built system can operate as a "benefical ruin" since it can be largely self-maintaining. Long-abandoned earthworks located throughout the world still function and help support pocket oases of vegetation. Examples in the southwest U.S. include check dams, terraces, contour berms, and stone mulches constructed by prehistoric Native Americans (see Real-Life Examples in chapter 7, and appendix 2 in Volume 1) and more recently by 1930s Civil Conservation Corps projects (fig. I.13).

Fig. I.13. A check dam built long ago atop bare bedrock has accumulated, upslope of the dam, a level terrace of soil and organic matter in which vegetation now thrives. The harvested soil and organic matter acts as a sand tank that quickly infiltrates stormwater flow, then slowly releases it to the plants' roots, and as a seeping spring flow over the bedrock that continues to run for weeks after the last rain. Anastasia Rabin enjoys a drink of this tasty water. Pima Canyon, Tucson, Arizona.

Each time I come across one of these old earthworks I find a lost world full of life. These unexpected treasures lure me to find more old sites and to create new ones—both in the wild and the city. I create a simple earthwork at the beginning of the rainy season, toss in some locally collected native seed or seedling followed by one good shot of water, then I'm gone. When I return months or years later I typically find more life than was there before, especially with urban tree planting projects. For these projects I advocate planting trees and spreading native wildflower seed in mulched water-harvesting earthworks. On average the trees planted within earthworks have about a 50% higher survival rate than conventionally planted trees without such earthworks. All trees benefit from initial supplemental irrigation, but those without earthworks often die when the person doing the watering quits or the irrigation system breaks down. In contrast,

trees and understory vegetation planted in earthworks live on even when supplemental irrigation stops because earth-worked soils hold water longer, and the basins receive additional water each time it rains.

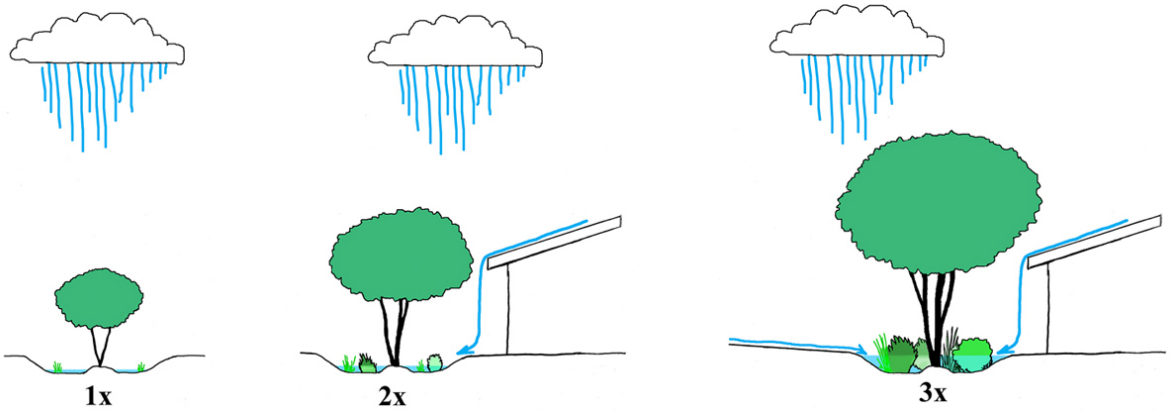


Fig. I.14. Available rainfall is captured within an infiltration basin, then *doubled* by also directing runoff (turned into run*on*) to the basin, then *tripled* by doubling the catchment area draining to the basin. Runon is right on!

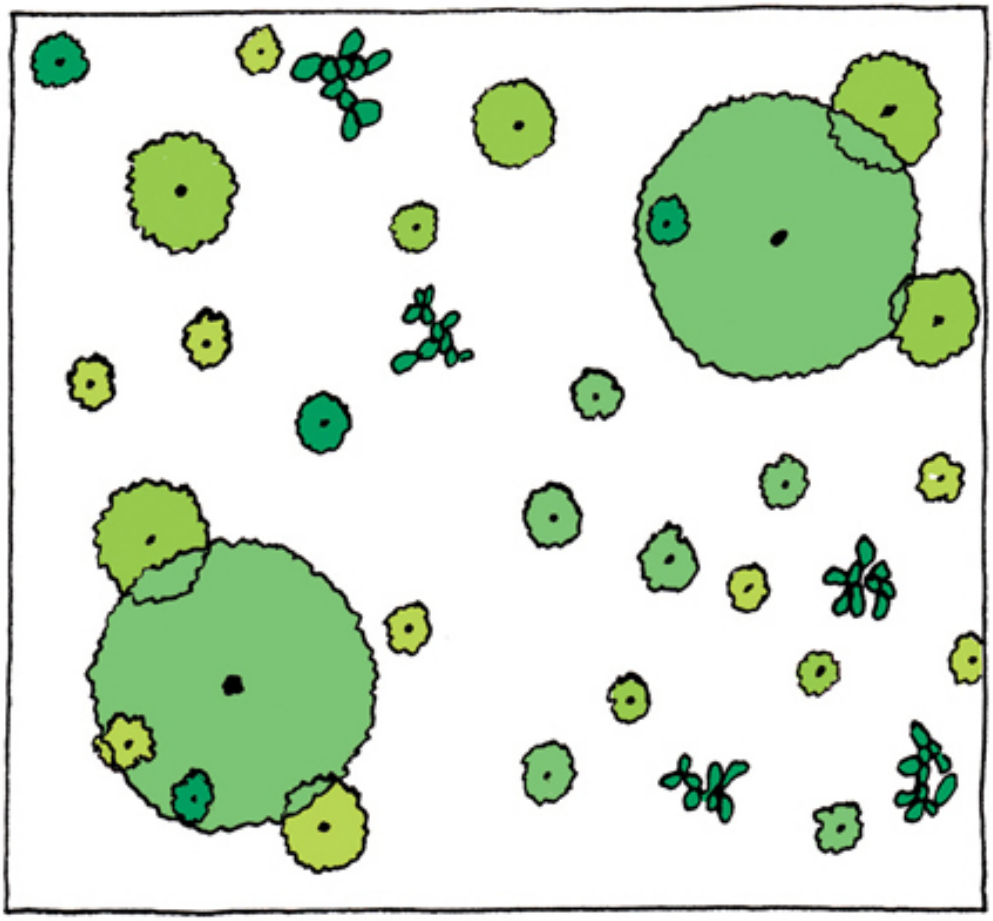


Fig. I.15A. Natural native-plant density *without* water-harvesting earthworks, when watered only by rainfall. View from above. Based on average annual rainfall of 12 inches (305 mm) on 1,000 ft^2 (92.9 m^2) of yard space, and estimates of plants' water needs from Volume 1 appendix 4 in Tucson, Arizona.

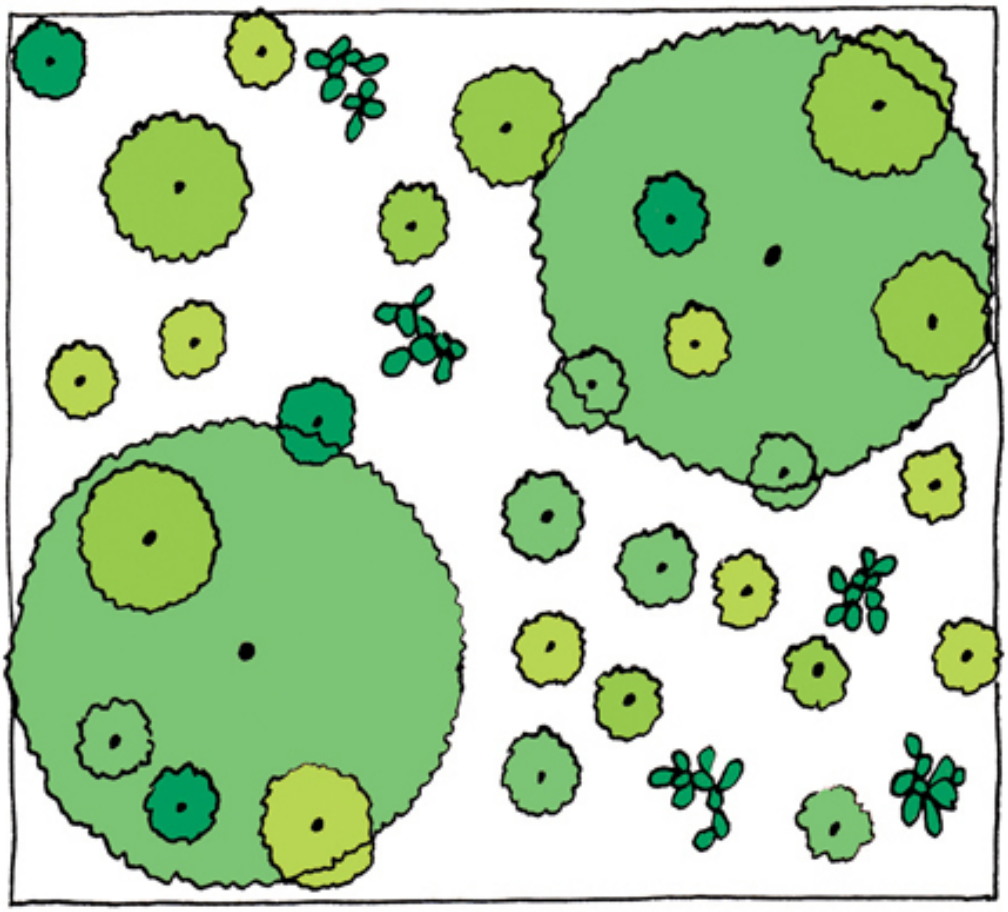


Fig. I.15B. Increased natural native-plant density *with* water-harvesting earthworks when watered only by rainfall. Based on average annual rainfall of 12 inches (305 mm) on 1,000 ft^2 (92.9 m^2) of yard space, and estimates of plants' water needs in Tucson, Arizona, from Volume 1 appendix 4. Greater plant size and density achieved by water-harvesting earthworks that increase the availability of rainfall to plants by reducing water loss to runoff and evaporation. Plant size and density could be increased further if runoff from an adjoining surface, such as a roof, street, or patio, and/or household greywater, were also harvested within the landscape's soil.

EARTHWORKS UTILIZE AND ENHANCE WHAT YOU HAVE ON SITE TO SAVE COSTS AND INCREASE POTENTIAL

Earthworks are best built using on-site materials such as soil, rock, and organic matter that naturally blend into the landscape. Salvaged materials, including chunks of old concrete, can look great when carefully formed into dry-stacked

walls (see chapter 4), porous paving, and one-rock dams. Existing native vegetation is planted in earthworks to the greatest extent possible because it is genetically programmed to burst into life exactly when seasonal rains fill basins. In areas where native vegetation is stunted due to lack of water, the addition of earthworks beside the plants can spur their growth from shrub-sized trees into shade-producing canopy trees. This can keep material and plant costs low to nonexistent.

EARTHWORKS HELP CREATE MORE SUSTAINABLE, FOSSIL-FUEL-FREE LANDSCAPES

Fully using on-site resources reduces or eliminates our need to import resources from off site. Not only is this less expensive and more efficient, but it reduces our on- and off-site consumption of dwindling fossil-fuel supplies and the pollution and global warming that threaten our future survival. According to scientists, we must reduce our carbon dioxide emissions by 70% (from 1990 levels) by the middle of this century to stabilize the Earth's climate. If we do not do this, we run the risk of disaster, as the rate of climate change will outpace the ability of ecosystems, food production systems, and economic development to adapt.[28]

While water-harvesting earthworks add abundance to the landscape by helping trees and other plants survive, they also help reduce energy costs and the use of fossil fuels, artificial fertilizers, and pesticides. Currently 5% of the electricity consumed in the U.S. is used to move water.[29] Earthworks decrease the consumption of fossil fuels (and the corresponding generation of CO_2) otherwise needed to pump water, fuel trucks, pipe water, and build the associated infrastructure. Earthworks combined with greywater harvesting also help reduce the energy-related costs of collecting, treating, and disposing sewage. Synthetic fertilizers, pesticides, herbicides, and "green waste" hauling are not needed when earthworks harvest onsite nutrient-rich organic matter and weed-suppressing mulch. Passive solar design in combination with growing earthwork-supported shade plants reduces energy consumption for conventional heating and cooling (see how to do this in Volume 1, chapter 4). This is sorely needed. According to *The Weather Makers*, 55% percent of the total United States domestic energy budget is devoted to home heating and air conditioning. Home heating alone costs Americans $44 billion a year.[30] Yet, I've repeatedly found that common-sense design strategies (described in Volume 1) can reduce costs to a fraction of what they are now.

See box I.3 for easy fossil-fuel-free landscape/garden choices (and see appendix 4 for additional resources promoting fossil-fuel-free strategies, and resources proactively addressing local and global climate change). Remember: Thriving gardens and landscapes existed long before we started using fossil fuels.

Box I.3. Material and Practice Choices That Can Increase or Decrease Our Fossil Fuel Consumption and Its Negative Side Effects

FOSSIL-FUEL-*CONSUMING* MATERIAL OR PRACTICE	FOSSIL-FUEL-*FREE* ALTERNATIVES
Municipal or well-water irrigation	Harvested rainwater, localized runoff, and greywater irrigation
Accessing and transporting irrigation water with plastic pipe	Accessing and transporting irrigation water with earthworks
Moving water with a mechanized pump powered by imported electrical energy or fossil fuels	Moving water with the free power of gravity, living pumps of vegetation and soil life, a ram pump, or alternative on-site energy source such as solar, wind, or micro-hydro
Virgin concrete patios and paths; decomposed granite or gravel groundcover that has been mined elsewhere and transported to the site	Raised and compacted patios and paths of on-site earth or mosaics of salvaged concrete chunks used as pavers; groundcover of organic mulch, preferably from local "green waste" or prunings cut up on site
Chemical fertilizers	Compost, nitrogen-fixing plants, leaf drop, cut-up prunings, organic fertilizers, local manure
Pesticides	Integrated pest management, beneficial insects, organic gardening practices
Herbicides	Mulch
Imported materials such as soil mixes, exotic stone or fired brick, wood from distant forests, and newly manufactured products	Local materials such as on-site amended soil, native stone or earthen building materials such as sun-dried adobe brick and cob, wood from urban/local trees, and used manufactured products reclaimed from the waste stream
Water-intensive plantings	Native and low-water-use climate-appropriate plants
Lawn	Drought-tolerant groundcovers
Ornamental plants	Multiuse food and medicinal plants
Power mower or weed whacker	Hand mower, grazing animals, getting rid of or greatly reducing lawn, hand weeding tools, mulch to keep weeds down
Power blower	Rake, broom
Power pruners	Hand pruning saw and hand shears
Home spa or hot tub	Cistern storing non-potable water, or go to beach, river, local water hole, or community pool or hot tub
Landscape lighting	Moon and star light; or dark-sky compliant, low-level, solar-powered lights
Hired labor driving to your site	Creating a more efficient landscape you can care for yourself
Driving to exercise in a distant mechanically heated and cooled gym and purchasing off-site resources	Exercising as you transport yourself by foot, bicycle, skateboard, etc.; exercising outdoors to maintain home and neighborhood, public landscapes, and gardens that generate on-site resources

This box was adapted from and inspired by "How To Go Fossil-Free in Your Garden" *by the Fossil-Free Landscaping Group, Santa Barbara, California, and Owen Dell (OwenDell.com).*

I GIVE THEE THY SHOVEL

Ready to harvest water? Go for it! The following chapters show you how to do it, whether you are doing the work or hiring someone to help. I advise my clients to begin harvesting water with earthworks because it is doable, fun, and effective. Just planting several native, low-water-use shade trees on the east and west sides of your home within or beside water-harvesting earthworks is a great start. The trees can grow to beautify, shade, and cool (by up to 20˚F or 11˚C) the area around your home in summer, while still letting the free light and heat of winter sun come in! Trees are natural, solar-powered air conditioners and heaters—and thanks to the earthworks, those trees, once established, will be watered just from the rain falling freely from the sky. Plant the rain. Plant life. And live within the constraints of your watershed. By doing so, you will give back more than you take. Over time your own landscape and the world around you will improve rather than become worse. When the mechanical irrigation system fails, the passive water-harvesting systems and the life that they support will live on. Move off the wasteful path to scarcity, and onto the stewardship path to abundance. And soon you'll be *dancing* in the rain!

Need still more inspiration? Read the following story.

REAL-LIFE EXAMPLE

EARTHWORKS TURNING WATER SCARCITY INTO WATER ABUNDANCE - RAJASTHAN, INDIA

I end this introduction with a story of how the Indian village of Laporiya turned wastelands into oases through water-harvesting earthworks, common watershed stewardship, and realization of the Eight Principles of Successful Rainwater Harvesting (see Preface for further description of the principles). While the scale and context may be very different from your site, this story illustrates the universality of the principles and how one person's local vision can be hugely magnified as ideas and efforts spread and infiltrate throughout our watersheds—like rain into the soil. For more water-harvesting success stories, urban and rural, big and small, in the U.S. and beyond, see the Real-Life Examples section at the end of chapters 2 through 12, and the epilogue.

A VILLAGE THAT PLANTED ITS RAIN AND WATERSHED

The water of the pastures is in the pasture
The water of the farms is in the fields
The water of the village is in the village

—A Sahalsagar village song touting the importance of harvesting the rain as close as possible to where it falls, by the people living closest to where it falls

After attending an international water-harvesting conference in Delhi, India, friends and I set out for the Thar Desert of Rajasthan to learn how people harvested water in the world's most populated desert. Our first destination was the village of Laporiya, but the drive there was unnerving. We saw a moonscape of bare soil and sometimes pavement. Our guide, Jagveer Singh, explained that the land was stripped of trees to make charcoal, denuded of grass by overgrazing, and encroached on by illegal mining and the building of houses and temples. On the horizon we saw farm fields of exposed windblown dirt. Some farms had been productive for a short time after bore wells were dug, but most wells had since dried up. The crumbling soil was eroded and salt-encrusted.

We drove farther, and thankfully the land dramatically started to green. We stopped at an odd concrete platform atop four 8-foot (2.4-m) posts seemingly placed in the middle of nowhere (fig. I.16). Nearby were numerous shade trees. We were now among the water-harvesting earthworks the villagers of Laporiya had built in their common pastureland. "What is that concrete structure for?" I asked. "A shady place for people to gather," replied Singh. "Why not just gather under the trees?" I asked. "Because when we started this work there were no trees."

Fig. I.16. In the background sits a concrete shade structure built for the villagers to gather and rest while they planned and built their earthworks. The earthworks now support the shade trees in the foreground.

In the 1970s the village of Laporiya was a drought-prone area of barren, saline soil, denuded pasturelands, and starving livestock. While summer rains once averaged 17–24 inches (440-610 mm) per year, a drought has kept annual rainfall below 8 inches (203 mm) since 1999. Nonetheless, Laporiya today is a relative oasis thanks to indigenous water-harvesting earthworks and communal stewardship of the local watershed.

Laxman Singh (elder brother of our guide) initiated the work. The nongovernment organization he organized, Gram Vikas Navyuak Mandal Laporiya (GVNML), and the village took it to completion.

Fig I.17. Yogesh Kumar, Laxman Singh, Ramkaran Poar, and Jagveer Singh of GVNML

Singh was born in 1956 when Laporiya was desolate. Though the son of the village chief, he had a rather impoverished childhood due to poor village land and water. At age 12 Laxman left for school in Jaipur, the capital of Rajasthan. Throughout his late teens he was troubled whenever he returned to his poor village. Families and animals were continually migrating away from the dismal conditions. At age 20 Singh decided to remain in Laporiya and work to improve it. He began farming 12 acres (5 hectares) of his father's land. It was tough work, and he often slept only two or three hours a night atop bullock carts to keep the animals from eating his crops.

After years of farming he became frustrated at the lack of improvement in the community's economic conditions and backward social practices. Laporiya comes from the local word *lapod*, meaning "mad." And Singh was determined the village would be known for more laudable reasons.

So, with a group of friends, Singh started a school, and taught the village youth in the evenings. This began to empower the youths who came to believe change was possible. This was the beginning of what would later become Singh's nongovernment organization, GVNML.

Singh wanted to reinvigorate the land. He spoke at length with village elders asking them what could improve the land, particularly the denuded common pastures. "Grass," they replied. But to grow grass there had to be water. The dying wells could not provide it, and most of the rain and soil washed away. He

watched the government build trenches and contour berms to harvest runoff, but these trenches concentrated water in local areas of pasture land rather than spreading it out to support widespread growth of grass. This initial *long and thoughtful observation* phase of Singh's learning showed him what was not working, and he set out to find and build examples that did work.

In the 1980s Singh traveled around India to visit traditional and revived water-harvesting and land-conservation projects, both large and small. One of these was an extensive project in the Alwar District of Rajasthan where five dry rivers were revived with perennial water flow after 650 villages built or rejuvenated 3,000 small earthen check dams and implemented community-led forestry projects that revegetated and "re-sponged" the rivers' watersheds.

The successes inspired Laxman Singh to return to his village determined to create water-harvesting strategies well suited to Laporiya's gradually sloping, degraded pasture lands. Based on his long and thoughtful observation of the land, consultation with village elders about monsoonal water flow, and his own observations of rain, soil erosion and soil deposition, Singh devised the chauka (square) system. This variation of boomerang berms (see chapter 3) consisted of a series of rectangular sections of pasture bounded on three sides with earthen berms about 3 to 5 feet (0.9 to 1.5 m) in height. The upslope, open side invites runoff in, while the berm retains this water, gradually spreading it throughout the whole chauka area, and cumulatively over the entire pasture encouraging water to *slow, spread, and infiltrate* into the soil where it is less prone to evaporation. Surplus water exits around the upper end of one of the side berms, then flows into an adjoining chauka slightly downslope. Overflow water flows from one chauka to the next until it is caught by an ephemeral watercourse that takes the extra water down to a natural monsoonal arroyo and a series of more distant earthen tanks or reservoirs. Every chauka has *an overflow route, and overflow from one chauka to the next is managed as a resource* ensuring each earthwork is filled before surplus water leaves the system (figs. I.18-I.22).

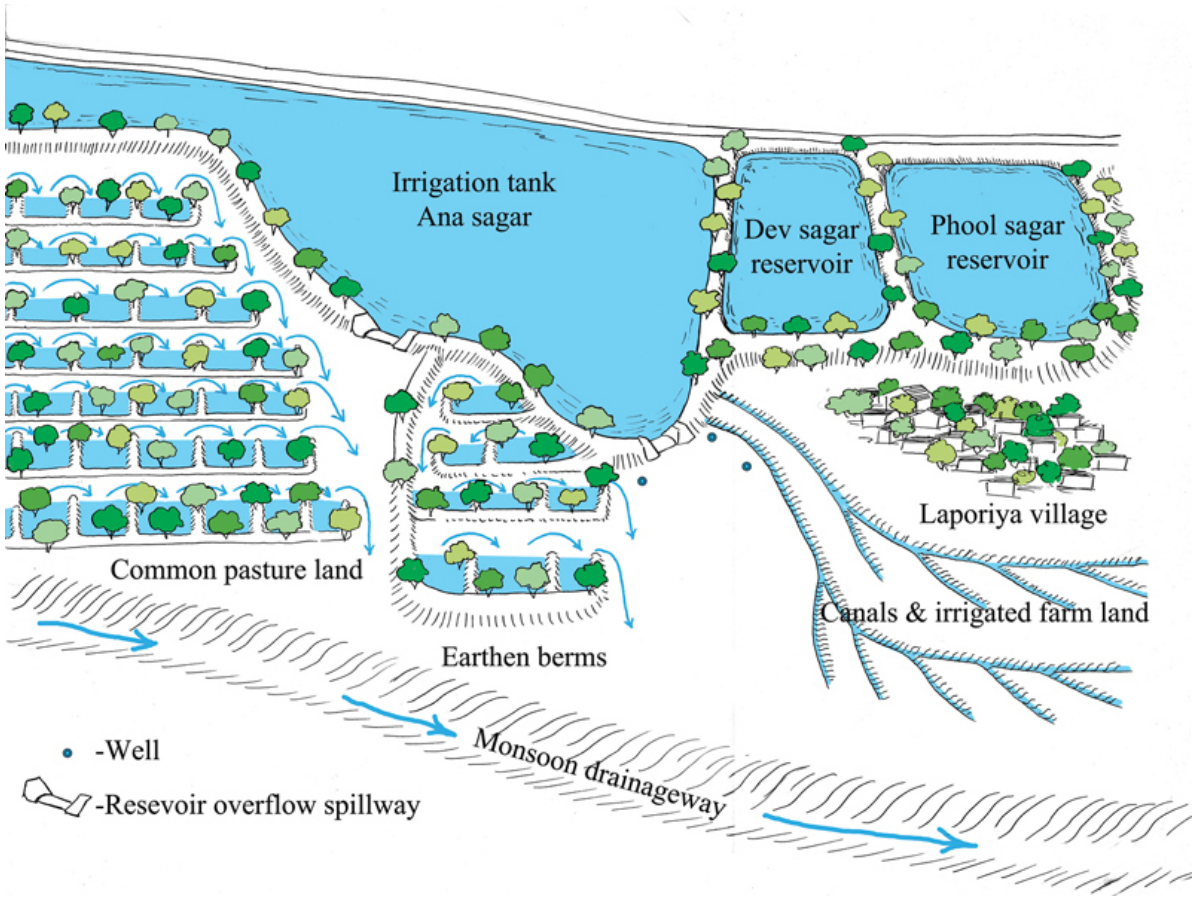


Fig. I.18. Map of Laporiya. The chaukas are the square berms in the common pastoral land seen at left side and center of figure. Arrows show overflow route of water. The irrigation tank and reservoirs capture runoff from their upstream catchments.

Fig. I.19. Goats browsing in pasture of chaukas in the neighboring village of Sahalsagar. Runoff flows in from right side of photo. Chouka berm on left stops the runoff and spreads the water back over the pasture to the right. The square basins upslope of the berm were dug out to obtain soil for the berm.

Fig. I.20. Sahalsagar chaukas. Slope is from right to left. Chouka in the background overflows to the chauka in the foreground, which overflows to another series of chaukas downslope to the left.

Fig. I.21. Chaukas full of water after rain. Credit: GVNML

Fig. I.22. Chaukas full of grass in the rainy season. The pastures with chaukas are productive even in years with just one-quarter average rainfall. Credit: GVNML

It took Singh three years of trial and error to get the chauka system working right, and he and the villagers continue to perfect the chaukas as they repeatedly work with and observe them—the eighth principle: *continually reassess your system: the "feedback loop*." If berms were made too tall and long, too much water covered the land and drowned the grass. If berms were too short and low, they harvested too little water and grass dried out. He found a 9-inch (23-cm) depth of harvested water to be ideal for local soils and native grass. Many of the chaukas on land with a 1% (0.6˚ or 100:1) slope are 656 feet (200 m) wide with side berms about 328 feet (100 m) long. The steeper the slope, the shorter the length of the side berms. The more gradual the slope, the longer the length of the side berms. To fix chaukas that were too far apart and collected too much water too deep, an extra chauka was placed between the two resulting in water being spread out to shallower depths in all chaukas. Singh *started at the top (high point) of the*

pasture's watershed and worked his way down. It was easier to manage smaller volumes and velocities of runoff, and he was able to *start relatively small and simple* with his experiments.

The chauka system has been found to be appropriate where there are relatively permeable soils and the slope does not exceed 3%. The chaukas spread shallow water over a larger area than the government-built trenches, promoting the growth of more grass (over 30 different species recorded thus far) and helping recharge the groundwater. Laxman got the soil for the berms by digging a series of level-bottomed, 1-foot (30-cm)-deep basins (for even infiltration of water caught within it) upslope of the berms. This created three distinct microclimates and moisture zones (like the rain garden planting zones presented in figs 11.12A-E of chapter 11): the drier berms, the wetter basins, and the flat areas in between. These supported a greater diversity of vegetation. Water-loving grasses for cattle and edible mushrooms for people grew in the basins. Camels go for the leaves of the trees that grow on and stabilize the berms, while acting as windbreaks. Goats roam the flat areas browsing on shrubs that also provide fruit for villagers. The diverse microclimates and growth created by the chaukas' topography has helped *maximize beneficial relationships and efficiency by "stacking functions"—the act of selecting and designing every element so it does at least three different things*.

But before Laxman Singh could get village support for the chaukas, he had to focus his efforts on the earthen tanks or *sagars* high in the village watershed. The tanks are the village reservoirs, and they harvest runoff from areas upslope of the village to supply accessible surface water for livestock and irrigation while recharging the adjoining wells that supply domestic drinking water (figs. I.23, I.24). Hand dug by the villagers generations earlier, they had since silted up and parts of the embankments had broken. Their capacity had been reduced to a fraction of what it once was, thus less water infiltrated the soil and more water erosively ran out of the watershed, contributing to sinking groundwater levels. Some villagers thought the government would fix the tanks, while others thought it was their destiny that the reservoirs be broken. So, in 1991 Laxman began to spread and sink the potential of proactive water harvesting in the minds of the people with a small and simple gesture. He began to repair the reservoirs himself, by hand, along with two youths from his GVNML village youth group. His example stirred the people. Seeing Laxman return each day to make tank repairs, more villagers began to join the work until, in the end, the entire village worked together to help repair the tanks.

Fig. I.23. The Phool Sagar earthen tank in Laporiya. Though full just after the summer monsoon rains, in the winter of 2005, a drought year, the bulk of the surface water has disappeared. Nonetheless, drinking water is available from the adjoining well year round thanks to monsoon rainwater, harvested and infiltrated into the soil.

Fig. I.24. The Phool Sagar earthen tank full of harvested monsoon water. Credit: GVNML

With this success the villagers were motivated to do more. Laxman then introduced them to the chaukas. Using volunteer labor, he initiated chauka construction on a 123-acre (50-ha) area of pasture land to assimilate the degraded land into a single protected unit. Existing paths used by people and animals were integrated into the chauka's layout to enhance pasture use rather than impede it—*stacking functions*. Once the chaukas were made, the compacted soil was plowed, and seed was broadcast just before the rains. Grazing was not allowed until the new seedlings were well established. When the villagers saw what they had done, they became believers. "Initially, we could not understand the chauka method," said villager Chotu Guzar, "but when the process was initiated we could visualize the result of the innovative plan."

However, the water-harvesting earthworks alone were not enough in Laporiya. The watershed had to be stewarded rather than exploited. The villagers needed to *maximize the living and organic ground-cover—the living sponge of the watershed*. The village met to decide how the land would be managed. They decided to ban the collection of manure from the pastures (dried manure is a preferred cooking fuel) so the land's nutrients could instead be recycled back into the soil. Hunting was prohibited. Cutting down native trees was banned, though coppicing, the selective pruning for wood, was allowed. If someone felled a tree, they needed to

plant two more, tender a written apology, and pay 11 pounds (5 kg) of grain. The villagers put up signs to notify outsiders of the work and the rules of the land. When I visited every family was required to plant five trees per year. This has since been increased to 10 trees per year. Shepherds tending their animals among the chaukas continually plant trees, shrubs, grasses, and other groundcover, the seed of which they collect year round to broadcast just before the rains.

Laporiya is now a village of diverse trees that provide shade, clean air, food, livestock fodder, wildlife habitat, medicinal herbs, fuelwood, and beauty. I found Laporiya to be the most vibrant of all the Rajasthani villages we visited over a four-week period. I loved walking the winding dirt roads and footpaths bursting with laughing children and healthy animals beneath a continual canopy of branches. Trees atop water-harvesting berms surround the fields and gardens (fig. I.25). During my stay, I was continually invited to drink tea and sweet buffalo milk beneath family neem trees beside the homes. Babui, keekar, tamarind, and amla trees, which have become rare elsewhere in Rajasthan, are abundant in Laporiya. Birds are everywhere. And, even in drought, shepherds surrounded by browsing goats showed off over a foot of soft, edible new growth in the shrubs and trees of chauka pastures. The villagers now produce a surplus of food, including 240,000 rupees' worth of milk sold each year by 200 families. Two crops a year, rather than one, can now be grown in rain-fed, rain-harvesting fields. Water levels in wells have risen from 60 feet (18 m) deep in 1991 to just 15 feet (4.5 m) beneath the surface now. Migration of families and animals out of the village has ceased.

Fig. I.25. An intensive, sunken, water-harvesting food garden surrounded by multiuse trees planted atop berms that also double as raised paths

Another of our guides, the enthusiastic Yogesh Kumar, pointed out deer in the pastures and the wild birds gathering in the center of the town explaining, "This is an open zoo—everyone, people and animals, can come and go as they choose. They are not sad in a cage, but happy and free." Villagers are encouraged to put water and seed out for wild birds. The reservoirs allow animals to drink and they can graze in the chaukas' abundant vegetation. In return, wildlife provides fertilizing manure complete with a diversity of seeds that grow into plants—nature as gardener.

In the center of town across the road from the gathering birds, you can view a map of this open zoo and its watershed (fig. I.26). It is a mural of the village's master plan delineating common land, private land, tanks, fields, and chaukas. Another mural delineates the village and who will manage what. It took 13 years to complete this planning process and get the whole village to agree. The plan is the culmination of the village taking ownership and stewardship over its resources and its future. It is the foundation of Laporiya's long-term success. As Singh

explained, “Social work must come before technological work because people can make or break any strategy.”

Fig. I.26. Ramkaran Pour and Jagveer Singh in front of a map of Laporiya’s water tanks, pastures, fields, and village. Jagveer points to Ana Sagar, the town’s earthen irrigation tank; beneath his arm are the common pastures treated with chaukas.

The story and strategies of Laporiya’s success had spread to more than 172 villages, and was benefiting over 330,000 people. But it’s now spread to over 600 villages. How? Through celebration. Every year on the eleventh day after Diwali, the Devuthni Festival takes place in and around Laporiya. For several days Laporiya’s 3,000 villagers march through neighboring villages promoting water harvesting, conservation of common lands, tree planting, and empowerment of the people (fig. I.27). The number of marchers grows each year, as villagers from some 50 other Laporiyainspired villages now participate. After marching there is a day of worship when people bless the water bodies they have dug themselves, anoint trees with the holy symbol tilak, and tie sacred threads or *rachis* around

each other's wrists and the trees, connecting them all and signifying the brotherhood of the villagers, their neighbors, the trees, and the watershed that supports and unifies them all. Everyone then takes an oath to steward the common resources of the village.

Fig. I.27. Villagers on the annual Dharti Jatan (Efforts for Earth) Padyatra foot march that celebrates the harvested waters and good work done, as it also brings communities together to discuss and address their collective needs. Credit: GVNML

Next follows a day of *shramdan*, voluntary labor to repair water-harvesting systems or create new ones. On the last day, 10 people are awarded the Diamond of the Land in recognition of their exemplary work creating or maintaining community water-harvesting strategies and vegetation in their village. The festival is a wonderful realization of the Eighth Principle: the "*feedback loop*" as people review the previous year's work and discuss future plans for forestation and enhancement of the local ecology. Of course, the celebration includes feasting,

dancing and song. “It is a rhythm of joy-discuss-joy-discuss-joy-discuss…,” guide Yogesh explained.

Laxman Singh calls this work the “road to livelihood.” And the feedback loop shows this work is a success. Each of the 103 wells in the village can now annually irrigate 2.5 to 5 acres (1-2 ha) even in drought. They no longer go dry as wells in neighboring villages without water harvesting still do. White salty soil and black sodic soils have been replaced with fertile soils supporting abundant vegetative growth. Local control of water and the watershed has returned. Rainwater harvesting vision and technology has “spread and sunk” among rural youth and citizens in the Laporiya-inspired villages, where more water is now put back into the land than is taken out. Government-supported green-revolution agriculture, dependent on deep wells, trucked-in water, and canal systems drawing from distant dying rivers, has been replaced with sustainable self-reliance, local pride, and ecological revival. It is the local ecosystem first and foremost that is the basis of Laporiya’s economy, quality of life, health, and happiness—the foundation on which we all ultimately depend.

For more information on the work of GVNML and Laporiya, see GVNML.org.

CHAPTER 1

Assessing Your Site, Choosing Your Earthworks, and Tips to Achieve Greater Success

The simplicity and complexity of harvesting water is it must be site specific.

—Shree Padre, Indian water harvester, farmer, journalist

This three-part chapter shows you how to work with, build on, and enhance the natural, free, living systems on your site to create a sustainable system of water-harvesting earthworks.

Part 1 builds on the water-harvesting principle of *long and thoughtful observation* and the site assessment tools described in Volume 1, chapter 2 and appendix 1, by helping you understand basic patterns of water flow over land and techniques used to "read" land slope. Both are key to getting to know your site. With this information you can select the earthwork strategies best suited to your site's needs.

Part 2 provides a quick go-to guide describing earthworks featured in this book. Scan the listed earthworks and their appropriate uses to see which might suit your site. Next, read the four important cautions applicable to all earthworks. When you are ready to hit the dirt, use the go-to guide (table 1.1) to direct you to the appropriate chapter that describes how to construct your selected earthwork(s) and provides case studies illustrating their successful use.

Part 3 provides 26 helpful tips to help you create regenerative rather than degenerative systems (see box 1.1). Building regenerative, integrated,

multifunctional earthworks will help ensure that your site gets better naturally as time passes, not worse.

Box 1.1. Creating Living, Regenerative Systems

By following the eight principles of water harvesting, passively irrigating your landscape with water-harvesting earthworks, and living within your site's water budget, you can create regenerative landscapes. Regenerative landscapes recreate themselves without depending on piped-in fuel or pumped-in water. Once established, they do most of the work so you don't have to.

Regenerative landscapes maximize the return on your water-harvesting investment. Anytime we invest effort, time, money, material, or labor we basically do so in one of three ways: degeneratively, generatively, or regeneratively.

A **degenerative** investment:

- Starts to degrade or break down as soon as it is made
- Requires ongoing investments of energy and outside inputs to keep it functional
- Consumes more resources than it produces
- Degrades the health of its surroundings and/or the world
- Typically serves only one function
- *Examples include*: ornamental lawns and landscapes dependent on chemical pesticides, fertilizers, and energy-consumptive irrigation water imported from wells, surface waters, o utilities—contributing to water extraction rates that exceed natural water recharge rates; mechanically heated, cooled, ventilated, and lit buildings powered by polluting imported energy; and conventional single-use parking lots

A **generative** investment:

- Starts to degrade as soon as it is made
- Requires ongoing investments of energy and outside inputs to keep it functional
- Produces more resources than it consumes
- Conserves other resources
- Typically serves multiple functions
- *Examples include*: multi-use landscapes (producing multiple resources such as food, beauty and wildlife habitat); passively heated, cooled, ventilated, and lit buildings; durable renewable, non-polluting energy products such as solar, micro-hydro, and wind-power systems (turning buildings and communities into clean energy producers, instead of dirty energy consumers); parking lots that grow a carport orchard of food-producing shade tree using harvested stormwater; and water-harvesting earthworks, cisterns, and gravity-fed plumbing that increase the multiple cycling and accessibility of on-site water resources, while conserving overall regional water and other resources.

A **regenerative** investment:

- Can repair and recreate or regenerate itself
- Starts to grow or improve once it is made
- Does not require ongoing investments of energy and outside inputs to keep it functional
- Produces more resources than it consumes
- Improves the health of its surroundings and the world
- Typically serves multiple functions
- Is *alive* or part of a living culture, that continually evolves/regenerates the investment

- *Examples include*: multi-use landscapes living solely off natural rainfall and stormwater runon, and requiring no additional outside resources after establishment, self-regenerating natural mulches, soils, forests and ecosystems; infrastructure, laws, and cultures maintaining equal access and rights for (and stewardship by) all—to such natural resources as the sun, prevailing winds, rainfall, and surface waters; revolving community loan funds building the capacities of individuals, their community, and its watershed; saving seed from each year's hardiest and most productive crops (then planting, and again saving seed year after year) to evolve a steadily hardier and more productive seed stock specifically adapted to the unique conditions of land and climate where you live; vegetative rainwater-harvesting structures that grow and repair themselves after establishment; and the songs and stories that help ensure the continuation of these progressing practices and investments.

Strive to make all your water-harvesting systems regenerative by working with, not against, the natural world. If you simply harvest rainwater passively, the way this book suggests, you'll rise from the degenerative to the generative level. Then keep developing and refining your system to bring it ever closer to the regenerative level.

PART 1: UNDERSTANDING PATTERNS OF WATER AND SEDIMENT FLOW, PLUS READING SLOPE

Water and sediment flow downhill, taking the path of least resistance. Therefore, the steepness and condition of a site's slope greatly affect the speed, depth, and volume of water that runs off the slope, plus the size and volume of sediment particles carried by the flow. The steeper and more bare the slope, the faster and more erosive the runoff, leaving concave landforms or depressions such as rills and gullies behind. The more gradual and vegetated a slope, the slower the runoff, the greater the infiltration, and the more likely that sediment will deposit, or drop out of the flow, creating convex landforms such as alluvial fans, debris dams, and depositional bars.

When sediment-laden runoff water is slowed or spread out, it loses the energy needed to carry sediment. The largest sediment particles—perhaps boulders in a really big flow—drop out of slowing water first. If the water continues to slow, ever-smaller sediment particles—such as smaller rocks, then sand, then clay—are deposited. The more slowly the water and sediment run off, the easier they are to manage. The more runoff infiltrates into the soil, the more the landscape is hydrated.

In unhealthy watersheds, erosion far surpasses deposition and can carve deep cuts in the land, leading to a rapid loss of valuable water, organic matter, soil, and

inorganic material. Thus, a deep, active erosion cut is a sign of an unstable landscape.

Natural drainages (healthy or unstable) are low places in the unaltered landscape where water collects and flows downhill. They function as overflows for the broader landscape. Whatever water and soil the landscape cannot hold, the drainages carry away.

Without a doubt, the best and most fun way to observe patterns of water flow and to read slope is to get out in the pouring rain and watch it flow across the land! But since dryland environments have relatively few rainy days, I offer three fun and effective techniques to understand, and work *with*, water flow even when it's dry:

- Bend over and look at the landscape and its horizon upside down through your This altered perspective gets your eyes closer to the ground and sometimes mak subtle slopes more obvious (fig. 1.1). And it gives onlookers something to wonc about!

Fig. 1.1. Water-harvesting mooning. Altering your perspective by looking at the landscape upside down sometimes makes subtle slopes more obvious.

- Use simple, inexpensive tools such as A-frames and/or water levels (sometimes called *bunyips*) to measure elevation differences and land slope. See fig. 1.7 and appendix 1 for details.

- Hone your observation skills for tracking water flow.

TRACKING WATER AND SEDIMENT FLOW

Water leaves tracks. Raindrops hitting bare soil erode it, and run off with some of it. While raindrops hitting dense vegetation atop soil are buffered and absorbed by plants and soil. Generally, life thrives where water lingers. Vegetation is denser, and topsoil is thicker and healthier, in areas where rainwater runoff flows slowly and soaks into the ground. Erosion occurs in places where runoff flows rapidly over the landscape, washing away soil and leaving vegetation stunted.

To learn to track water, carefully observe water flowing, pooling, and infiltrating during and immediately after a heavy rainstorm. Also look for how much sediment is moving in that water. Is the water clear, cloudy, or muddy? Return after the water and sediment stops flowing and pooled water has soaked into the soil. Examine these same areas. Notice whether organic matter, clay, sand, and rocks have accumulated or have been washed away. Envision water flowing in these places to directly compare erosion, deposition, and other tracks left by flowing water to your observations of active water and sediment flow noted minutes or hours before.

Water and sediment flow over the landscape often takes the form of a branched system, similar to the branched circulatory system of our bodies. At the top of all watersheds are very small branches not easily recognized, like the microscopic capillaries within our skin. They are the tiny air spaces within the soil, rock, organic matter, and vegetation covering the watershed. Runoff forms when these tiny "capillaries" in the soil and vegetation are saturated, and water begins to flow over the surface. As water runs farther down a slope, more surface runoff collects, and the upper branches of the watershed become noticeable. You see slight depressions and small drainages where more of the runoff begins to concentrate and flow downhill. Continuing downhill, these small drainages merge to become washes, wadis, arroyos, or creeks (fig. 1.2). These larger branches combine with others, eventually merging into rivers, and then deltas that transition into lakes or seas. The larger the branch (or vein), the higher the volume of water moving through the system.

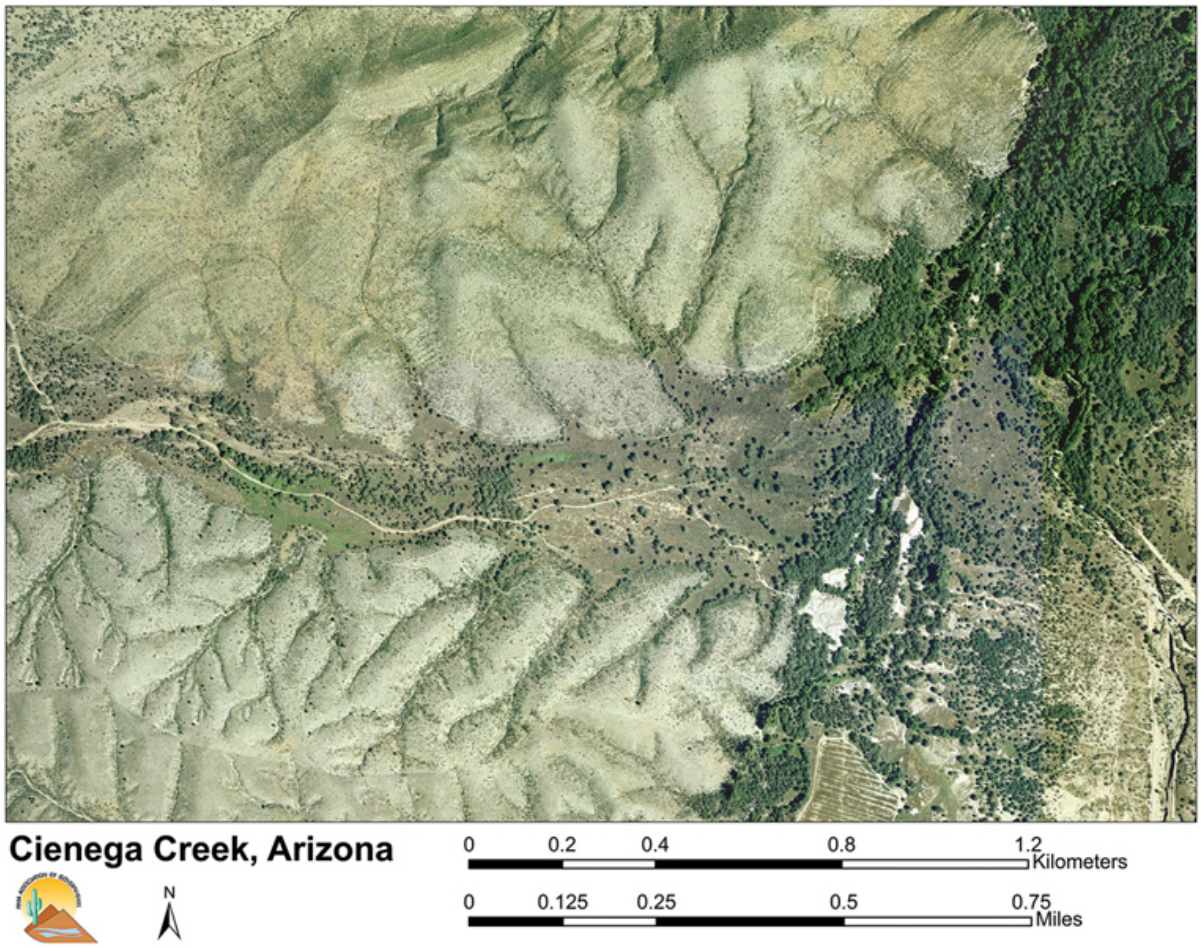


Fig. 1.2. Aerial photo of dendritic pattern of branching watercourses at Cienega Creek, Pima County, Arizona. Note how water drains off the dry, sparsely vegetated ridges into small drainages that combine with others as they move downslope, eventually merging into the larger, densely vegetated Cienega Creek below. Aerial photo provided by Pima Association of Governments

Identify the capillaries of your watershed, then follow the first principle of water harvesting: *start at the top (high point) of your watershed and work your way down.* The capillaries are the headwaters—or top—of our watersheds where the lower volume and velocity of runoff and the sediment it carries are easily managed. The capillaries of a community watershed are very often the small drainages and small subwatersheds of our backyards, school grounds, neighborhood streets, and work places. Many small efforts made here—vegetation, an earthen berm, a band of rocks planted/laid across a slope, or infiltration basins for trees—can cumulatively make a big difference. It's easy and we can all do it!

To leverage that capacity to be more effective, positive, and dynamic, continually ask yourself:

"How is the water flowing across this site?"
"How will (and how are) my interventions affect(ing) that and other flows?"
"What is the desired effect of my efforts?"
"How can my approach better *align* with natural flows of water, sediment, and more, in a way that enhances this system's ability to improve its own health and that of the larger watershed(s)?"

Such questions push us to look for, see, understand, and work *with* natural patterns—making it easier to innovate and cooperate with the living systems active in the unique context of our site, rather than just imposing a generic or rigid strategy.

The erosion triangle helps bring a number of these patterns to light, so I always use it along with the water-harvesting principles to determine what water-harvesting earthworks may be appropriate to use and where (fig. 1.3).

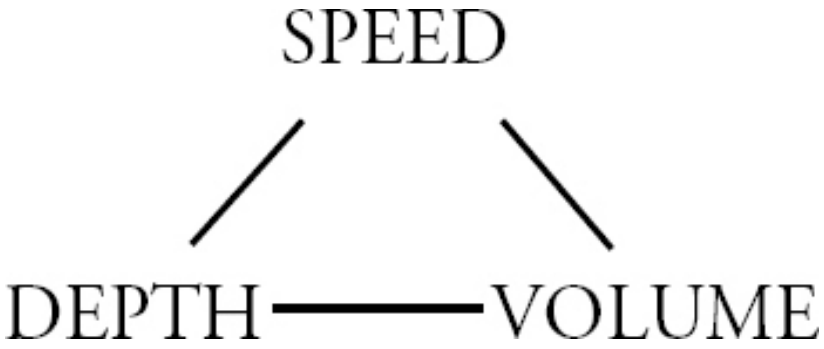


Fig. 1.3. Erosion triangle

SPEED, DEPTH, and VOLUME refer to three characteristics of water flowing on the broad surface of the land and within channels. *Reduce* any of the three by **slowing**, **spreading**, and/or **sinking** the water's flow, and you begin to break the erosion cycle. The more places you break the cycle, the more you *reduce* erosion. If you put a water-harvesting strategy— such as a berm 'n basin (chapter 3), one-rock dam (chapter 10), infiltration basin (chapter 2), and vegetation—in the path of flowing water, you will *decrease* erosion by *decreasing* the SPEED of water flow, thereby *increasing* the time the water has to linger, cycle, and **sink** into the earth below, where it becomes available to support the growth of plants. The more plant life the harvested water supports, the more roots hold the soil, the more plant canopy shelters the soil, and the more biomass catches and builds the soil. Your efforts will help generate many living "speed bumps" on the erosion highway.

The *greater* the DEPTH of flowing water (not stationary, pooled water) at any given point, the *greater* the water's power to erode and carry sediment, compared to shallower water moving at the same speed. Numerous water-harvesting strategies placed top to bottom throughout a watershed to **spread** the water's flow will *decrease* erosion by *decreasing* the DEPTH of flowing water. At the same time, **spreading** the water *increases* the duration and surface area of contact between water and earth, *increasing* the quantity of water **sinking** or infiltrating into the subsurface. Water that **sinks** into the subsurface migrates laterally and downward through the force of capillary action and gravity. This leads to longer-duration water storage and higher soil-moisture availability than occurs when water flows rapidly across the land surface or within channels and quickly evaporates.

The *greater* the VOLUME of water flowing over land or within a channel, the more sediment it can carry. If you place a number of water-harvesting and water-infiltrating strategies boosting vegetation starting at the top of the watershed, you will **sink** a larger quantity of water higher in the watershed, *reducing* erosion by *reducing* the overall VOLUME of unchecked surface-water flow throughout the watershed. With *more* contact time and contact area between water, earth, and plants; *more* water will be absorbed into the subsurface. This is like placing speed bumps from the top of a watershed to the bottom so the water never gets a chance to destructively speed up and accumulate in an unmanageable VOLUME.

As you read on, learn about, and consider the use of various earthworks, imagine how those earthworks and the life they support will affect the erosion triangle. Very often you will be trying to **slow**, **spread**, and **sink** water flow, thus *reducing* its SPEED, DEPTH, and/or VOLUME.

But sometimes you might instead want to increase the SPEED, DEPTH, or VOLUME of flowing water at a certain location, such as at a curb-cut inlet to a street-side water-harvesting basin (chapter 8). If you were to **slow** the flow of street runoff at the cut in the street curb, sediment would drop out of the flow at the curb cut and clog the system, leaving the downstream basin and its vegetation dry. Is that the desired effect? No!

But if you instead *increase* the SPEED of flow at the curb cut, by perhaps increasing the slope at the inlet (and/or you increase the VOLUME of flow by *increasing* the width of the inlet) water would pass through with more energy or force, carrying sediment through the inlet, rather than dropping sediment out, clogging the inlet. Is that the desired effect in this context? Yes!

When you *increase* the SPEED or VOLUME of water flow through your curb-cut inlet, you must then address the *increased* erosion potential of the steeper slope below this inlet. The slope could be stabilized with an impervious concrete channel, but if the larger desired effect is to facilitate more life, more infiltration of water, and natural filtration or bioremediation of street runoff pollution, then it would likely be better to stabilize the slope with a more porous strategy, such as a single course of well-placed rock (a rock-mulch rundown—chapter 10, Variations), or vegetation.

Simultaneously consider the big and small pictures. For example, a contour berm n' basin (chapter 3), which is intended, in the big picture, to **slow, spread**, and **sink** water flowing into it from the broad landscape above, might flip that effect at its overflow spillway if the overflow is discharged over a steeper slope or is unduly constricted/concentrated—thereby *increasing* the SPEED-DEPTH-VOLUME at the overflow. Make sure you understand potential cause and effect—using the erosion triangle—and design accordingly.

Don't be intimidated by this—be liberated. Observation will tell you all you need to know about what is happening in the unique context of your site. You can then choose a course of action(s) best suited for the unique needs and potential of your site. This is site-specific work. Observation reveals the on-site patterns. Pattern recognition informed the water-harvesting principles (and can inform new ones as your understanding evolves). The principles then guide us to better align our actions with those patterns, leading to a better-informed choice, innovation, and hybridization of potential site-specific strategies. Pattern –> Principle –> Strategy.

When unsure, remember that the principles have your back. That's why the second principle is *start at the top of the your watershed and work down*. The top is where all this is so much easier due to smaller, calmer flows. This also enables you to realize the third principle, *start small and simple*—mistakes are easily fixed at that scale and are therefore learning opportunities, not catastrophes.

See appendix 1 in Volume 1, 2nd Edition for illustrations of more water-, erosion-, and deposition-flow patterns; their causes; and how these patterns might change in response to various water-harvesting earthworks. The section below will help you identify the slope of a site to further guide you in selecting site-appropriate earthworks. Table 1.1 summarizes a range of water-harvesting earthworks to choose from. These strategies are described in detail in later chapters of this volume.

HOW TO MEASURE AND DESCRIBE SLOPE

Because proper earthwork selection and placement depends on the slope of a site, it is helpful to know how to measure and describe a slope. Three common methods of measuring and describing slopes are described here: proportions, degrees from horizontal, and percentages. Choose the method that is most useful for you.

Proportion is the ratio of a slope's horizontal distance to its vertical distance. This is my favorite way of measuring slope, since I find it intuitively gives people a mental image of the slope. A 3:1 slope extends out a horizontal distance of 3 units, while rising a vertical distance of 1 unit. You choose which unit of measurement to use for your proportions (English or metric). For this example let's use feet, so the slope extends horizontally 3 feet for every 1 foot of vertical rise. Note: When using proportions, it is important to be clear which unit represents the vertical and which represents the horizontal, since some folks list the horizontal first, as I do, and some list the vertical first. See box 1.2 and fig. 1.4.

Degrees from horizontal is a measurement civil engineers often use to represent the angle of a slope from horizontal. A site that is 0° from horizontal is a flat level site. A site that is 90° from horizontal is a vertical cliff. All sites lie somewhere between the 0° to 90° range. A slope with a vertical drop of 1 foot over a horizontal distance of 3 feet is 18.4° from horizontal. See figs. 1.4 and 1.5.

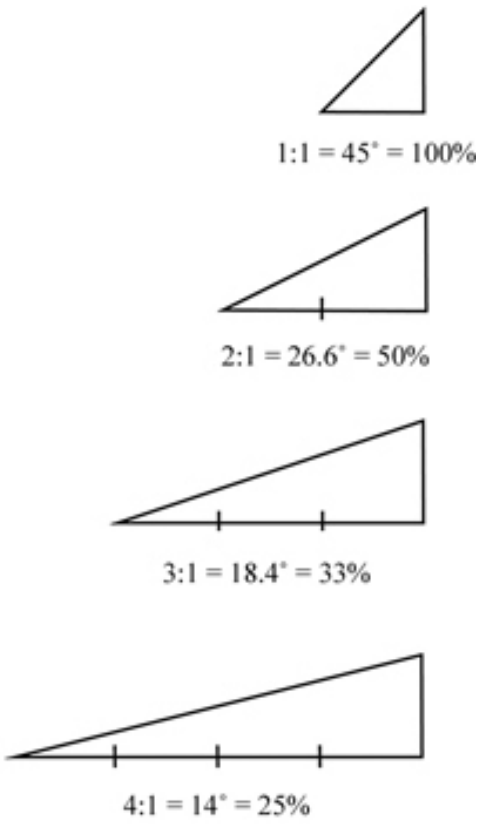


Fig. 1.4. Four different slopes measured by proportions, degrees from horizontal, and percentages

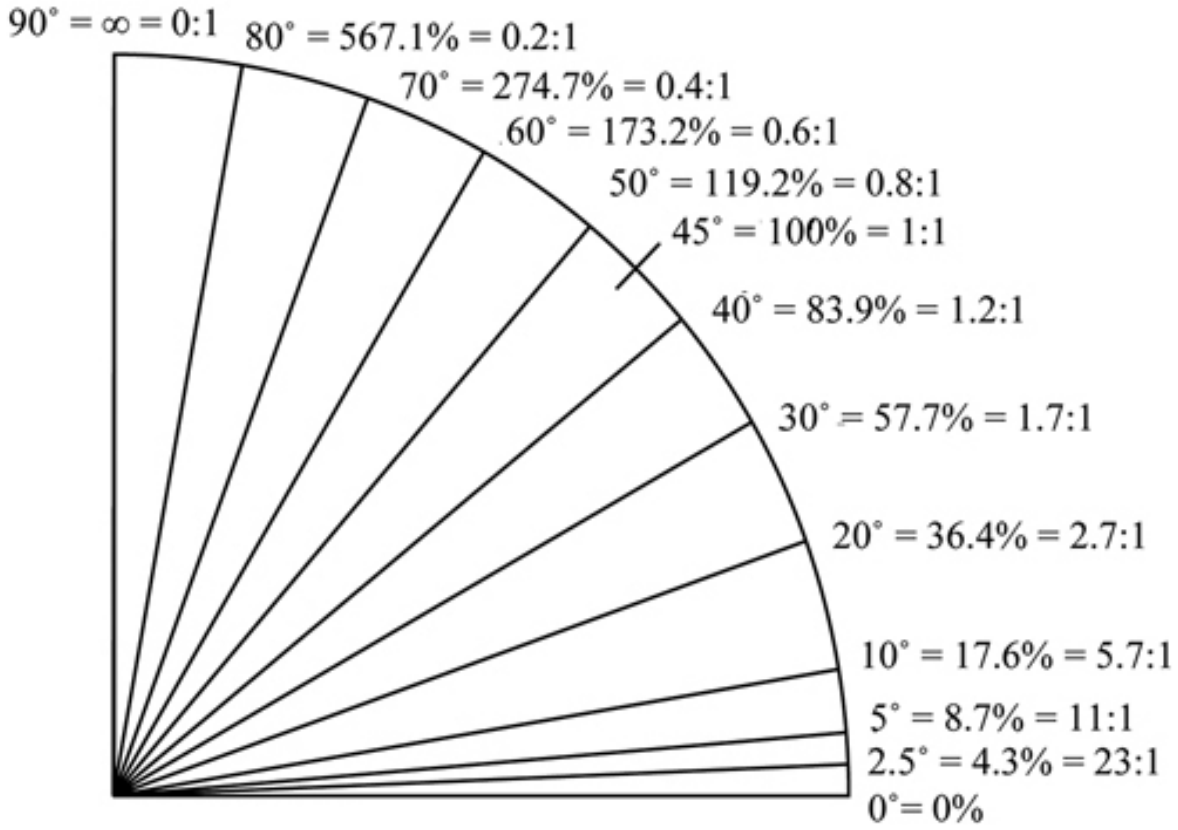


Fig. 1.5. A range of slopes from 0° or 0% up to 90° or infinity

Slopes expressed as percents are calculated by multiplying the distance of vertical rise of a slope by 100, then dividing that figure by the horizontal distance covered by the slope. For example, a slope with a rise of 1 foot over a horizontal distance of 3 feet is a 33% slope (1 × 100 ÷ 3 = 33%). A slope with a rise of 1 foot over a horizontal distance of 1 foot is a 100% slope (1 ý 100 ÷ 1 = 100% slope). Slopes measured in percentages range from 0% for a horizontal line to infinity (∞) for a vertical line projecting straight up. See figs. 1.4 and 1.5.

Box 1.2. How to Take a Measurement of a Slope

To take a measurement of a slope, you measure the vertical rise of the slope as it relates to horizontal distance of the slope. Two easy ways to do this are to use a string, a line level or carpenter's level, and a yard stick or tape measure (fig. 1.6); or to use a bunyip water level (fig. 1.7).

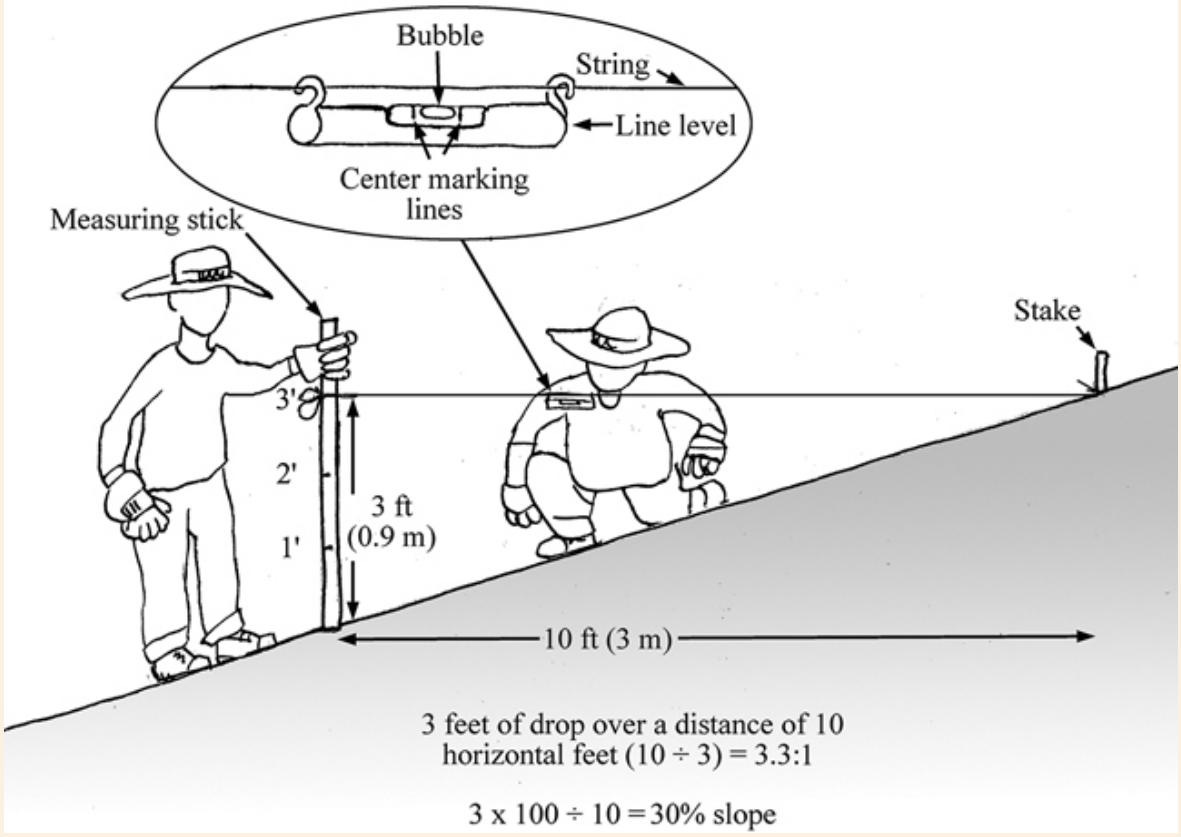


Fig. 1.6. Using a line level to measure slope. Hold or stake one end of a string on the upper side of a slope you want to measure. Walking directly downslope, pull the string tight to a set length (such as 10 feet or 3 meters), and place a line level in the center of the string. Raise or lower your end of the string until the line level's bubble is centered between its center marking lines, indicating the string is level. (You could also use a carpenter's level to check the level of the string.) Then use a tape measure or measuring stick to measure the height above land surface of the level string to find out the vertical rise of the slope.
Adapted from *Food from Dryland Gardens* by David Cleveland and Daniela Soleri, Center for People, Food, and Environment, 1991

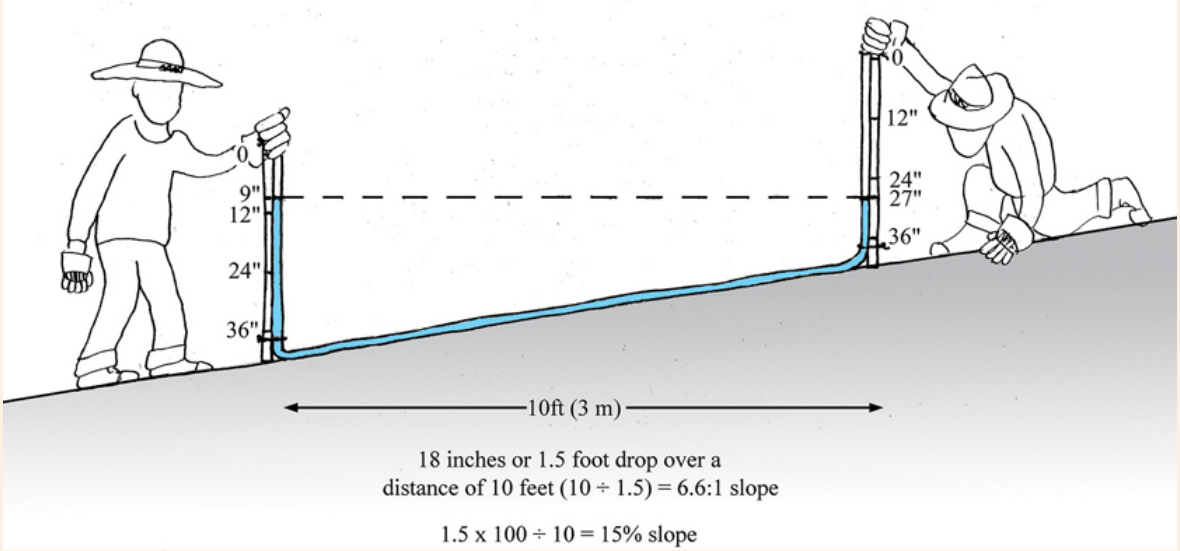


Fig. 1.7. Using a bunyip water level to measure slope. The difference in *water level* measurements in water-filled transparent tubing attached between two stakes marked with identical scales is the vertical measurement used to determine slope. The bunyip reads 21 inches on one stake and 9 inches on the other. 27 - 9 = 18 inches or 1.5 feet of vertical distance between the upper point on the slope and the lower point on the slope. The horizontal distance between the *two stakes* is the horizontal measurement used to determine slope. See appendix 1 for more information.

PART 2: SUMMARY OF WATER- HARVESTING EARTHWORKS

What follows is a quick reference guide. Table 1.1 briefly describes all water-harvesting strategies featured here and leads you to the chapters that cover them in detail. Chapter 3 contains a detailed discussion of design, calculations, and construction of the berm 'n basin technique. Chapter 3 also provides an important foundation for understanding all the other water-harvesting earthwork techniques. Read it thoroughly, and go back to it as you read about and implement other earthwork strategies.

Note that there are many more water-harvesting earthworks than those featured here, but most can be classified as variations of the earthworks I feature. In fact all the separate earthworks described here could be classified as variations of one another because they all strive to check runoff and harvest rain, snow, and runoff in the soil. I provide many earthwork strategies and case studies to help you to

choose what is best for your site's unique conditions and to empower you to create your own variations.

Note: *Green roofs or eco-roofs* (roofs covered with soil in which vegetation is grown) are not covered in this book. They can be a great strategy, especially in urban environments short on unpaved soil, but because they are constructed on top of buildings rather than within soil at land surface, I do not consider them a typical earthwork.

Table 1.1. Quick Reference Guide to Water-Harvesting Earthworks

EARTHWORK STRATEGY AND CHAPTER	WHAT IT IS	GOALS	WHERE TO USE	CAUTIONS SPECIFIC TO STRATEGY	VARIATIONS
Infiltration Basin Chapter 2	Shallow level-bottomed depression dug into earth	Intercepts and infiltrates rainfall, runoff, greywater, and condensate	Flat to gently sloped land. Intercept runoff from multiple or all directions. Size for maximum storm event and peak surge of greywater. Do not use in drainageways.	NOT appropriate in areas of shallow groundwater where they might result in standing water, or over septic drain field.	- Basins around existing vegetation - Berms forming basins around existing vegetation - Sunken garden beds - Raised sunken beds - Irrigation pots or ollas
Berm 'n Basin (b'nb) Chapter 3	Berm set perpendicular to slope, typically made of earth excavated to form adjoining upslope basin	Intercepts and infiltrates runoff in localized area	Use on land sloped up to 3:1, 18°, or 33% grade. Size for maximum stormwater event. Do not use in drainageways.	Try to preserve what existing vegetation you can. Earthen b'nbs not appropriate in areas of high sediment in runoff	- Contour berm - Boomerang berm - Net and Pan - Contour plantings
Terrace Chapter 4	Relatively flat "shelf" of soil built parallel to contour on slope	Creates level planting area to intercept direct rainfall and some runoff from slope	Slopes up to 2:1, 27°, or 50% grade. Size for maximum storm event. Do not use in drainageways.	NOT appropriate in soils prone to waterlogging or areas with perched aquifers	- Terrace with a retaining wall - Terrace without a retaining wall - Salvaged concrete or *urbanite* terrace walls
Infiltration Trench Chapter 5	Trench or basin filled with porous rock, organic material, or bottomless infiltration chamber	Infiltrates intercepted rainwater quickly into subsurface while maintaining flat walking surface	Flat to gently sloped land where deep infiltration is needed. Intercept only sediment-free runoff water (e.g., runoff from roof, paved patio, driveway, etc.). Do not use in drainageways.	NOT appropriate in areas with sediment-laden water or beneath or across roadways. Majority of infrastructure is out of sight, so is more difficult to catch and fix problems	- Infiltration trench without pipe - Infiltration trench with pipe - Infiltration trench with infiltration chamber - Deep pipe irrigation - Rock tube irrigation - Structural soil - Soil cell
Imprinting Chapter 6	Revegetation strategy using numerous micro-imprints/depressions	Collect seed, rainwater, sediment, and plant litter to create favorable microclimates for seed germination and growth	Flat to sloped land up to 2:1, 27°, or 50% grade. Use on abandoned fields, building sites, rangeland, soils with rock up to one foot in diameter. Need > 1 acre to justify mechanical imprinting. Do not use in drainageways.	More effective when integrated with other water harvesting/spreading strategies such as contour rock berms/sheet flow spreaders and perennial vegetation	- Mechanical imprinter equipment varies for steep slopes and rocky soils. - By hand—zai planting pits - With animals—intensive, short-duration herding, dunging, urinating
Mulch Chapter 7	Application of porous organic or mineral materials to soil surface (e.g., compost, aged manure, straw, wood chips, gravel)	Increase infiltration rate, improve soil fertility, reduce evaporation loss, limit soil erosion, suppress weed growth, delineate basins from paths	Mulch soil inside water-harvesting earthworks. Do not use in drainageways. Organic matter mulch is typically superior to rock/gravel mulch where more soil moisture and carbon sequestration is desired	Slow or stop runoff before contact with mulch. Mulch thickness should not exceed what will become saturated in an average storm. Avoid soil-sealing unwashed decomposed granite in earthworks.	- Surface mulch - Vertical mulch - Mulch contour berms - Concrete *drainageway* jackhammered into cobble *infiltrationway*

Reducing Hardscape, Harvesting Its Runoff, and Creating Permeable Paving Chapter 8	Planning and design strategy to increase water infiltration by reducing nonpermeable hardscape, capturing hardscape runoff within adjoining landscape, and replacing nonpermeable paving with permeable paving or surface material	Reduce heat island effect, soil dehydration, and flooding. Increase water infiltration, maximize living shade canopy over pavement, and contain and bioremediate pollutants on site	Where you have pavement. Permeable paving useful on densely developed sites with little unpaved surface. Most effective when harvesting rainwater that falls directly on it, not runoff from upslope areas. Do not use in drainageways.	Raise permeable paving above the surrounding landscape to prevent settling or pavement displacement due to poorly draining subsoil. NOT appropriate in areas receiving sediment-laden runoff.	- Pavement reduction & shading - Broken pavers - Grid-stabilized soil or gravel - Permeable concrete pavers - Porous concrete - Stabilized earth or crushed rock - Curb cut - Curb core - Eddy basins with and without pipe - Green streets and parking lots
Diversion Swale Chapter 9	Curvilinear basin or swale constructed slightly off land contour	Gently and gradually move water downhill and across a landscape, while promoting infiltration into the soil	Diversion swales direct runoff to water-harvesting earthworks, or tame the force of water from culvert or roadside bar ditch. Can use diversion swales as water inlet and drain channel bookending agricultural irrigation bays. Direct overflow water from one water-harvesting earthwork to another. Do not use in drainageways.	Do not use in alkaline soils prone to salt buildup or waterlogging.	- Diversion swale - Spreader drain - Rolling dip dirt road drain - Connect and spread - Daylighting buried waterways - Keyline pattern cultivation - Farm fields as floodplains
In-Channel Strategies Chapter 10	Mimicking natural patterns of healthy water and sediment flow with conservation strategies to stop erosion; and restoration strategies used to restore or regenerate healthy watercourse bed elevations, connection with floodplain, and channel ecologies	Spread flow to increase infiltration and duration of flow, reduce erosion, improve water quality, and grow vegetative stabilization	Within water channels having beds and banks with ephemeral or intermittent flow, rather than perennial flow. Can address rills, gullies, and eroding arroyos; stabilize roads or paths across drainages; reduce erosion below culverts; and restore wetlands, springs, and floodplain connections. Appropriate in areas of high sediment in runoff.	May need regulatory approval to work in watercourses. Placement and correct construction is critical to avoid damage.	- Rock-mulch rundown - Sheet flow collector - Rock-lined plunge pool - One-rock dam - Filter dam - Sheet flow spreader - Induced meandering - Beaver
Vegetation Chapter 11	Along with soil microorganisms, it's the living element of all earthworks that anchors, builds, and shelters soil while regeneratively producing resources	Increase infiltration, support or produce new plant life, soil microorganisms, wildlife habitat, food, fiber, forage, building materials, shelter, medicine, erosion and dust control, water storage, carbon sequestration, and much more	Plant within and beside all earthworks, throughout watersheds, from flats to slopes. Plant climate-appropriate species at densities that can primarily, or solely, subsist on the harvested rainfall, runoff, and/or greywater. Can plant within drainages if stabilizing banks and bed without detrimentally impacting flow	Locate and space plants based on expected mature size, water needs, water sources, and tolerance to inundation. Keep root crops away from greywater. Beware of invasive exotics.	- Planting within basin - Planting on a slight pedestal within basin - Planting beside basin - Rain garden planting zones - Planting guilds - Planting rain then seed—all in situ

FOUR IMPORTANT POINTS OF CAUTION FOR ALL EARTHWORKS

1. A good general rule, and a recommendation in the International Building Code, to *not* infiltrate water in the soil within 10 feet (3 m) of a building's foundation. (This does not include cisterns.)[1] This ensures that you do not weaken the struct by disturbing soil within the 45° angle of compressive force emanating from the

footing. Staying this distance from the structure also reduces the risk of saturatir the soil under the building and avoids creating a habitat right at the base of the building where moisture-loving termites would thrive. Instead, provide moisture termites out in the landscape where these "earthworms of the drylands" will exp turn fallen leaves and dead plant matter (not your house) into fertile, porous soi

2. Always check for underground utility lines before you dig and strictly avoid any areas where these do, or might, exist. Rupturing a gas line will ruin your day, guaranteed. There is a free service that will mark all utility lines running from th street to the meter at your site. Call 811 at least four days before you dig.

   The utility lines running from the meter to the house *will not* be marked by these free utilitylocator services, but they can be located by a private locator service for a fee. It is very important that you locate all underground utility lines at your site. Also, to avoid future problems, do not plant trees where they could grow into overhead utility lines.

3. The water-harvesting strategies presented here can generally be designed and implemented without having a registered engineer analyze the situation and prepare the design. However, if any of the following conditions exist, you need to hire a registered engineer and/or consult with a geologist:

   - You are working in a regulated drainage
   - An expensive asset (like your house) could be affected by the design
   - The work might affect neighboring properties
   - You are dealing with steep or unstable slopes
   - You are in an area prone to mudslides
   - Any other circumstance you feel uncomfortable with, or situations that might b creating a risk for yourself or others

   If hiring these professionals is not an option, then reduce, simplify, or modify your project so such help is not required. You are ultimately responsible for the work you do on your site.

4. Follow *all* water-harvesting principles and ethics summarized in this volume's preface, and thoroughly described in Volume 1, chapter 1.

Note that the principle of *start small and simple* can expand with knowledge, experience, and the scale of a project. For example, in a master-planned community a well-designed and implemented series of street-side runoff-harvesting basins and plantings ("natural drainage systems"—see chapter 8) could be utilized throughout the development and its watershed. While individually the strategies are small, cumulatively they are large, and are much more effective than a large retention/detention basin(s) focused at the bottom of the site's watershed.

PART 3: TWENTY-SIX WATER-HARVESTING EARTHWORK TIPS

1. FOLLOW ALL OF THE "EIGHT PRINCIPLES OF SUCCESSFUL WATER HARVESTING."

See this volume's preface or Volume 1 for these principles.

2. FOLLOW THE "FOUR IMPORTANT CAUTIONS."

3. START WITH JUST ONE OR TWO SMALL SIMPLE EARTHWORKS.

Watch to see how small-scale earthworks function in the next big rain. Use lessons learned at this scale to guide your work with more extensive water-harvesting earthworks.

4. PLACE YOUR EARTHWORKS WHERE THEY, AND THE VEGETATION THEY SUPPORT, WILL CREATE THE GREATEST NUMBER OF BENEFICIAL FUNCTIONS AND RESOURCES.

For ideas, see the integrated design patterns from Volume 1, chapter 4: the solar arc, maintaining solar access, and raised paths and sunken basins (see figs. 1.8, 1.9, 1.10, 1.11, 1.12). And refer to the multiple-functions sections of chapters throughout this volume.

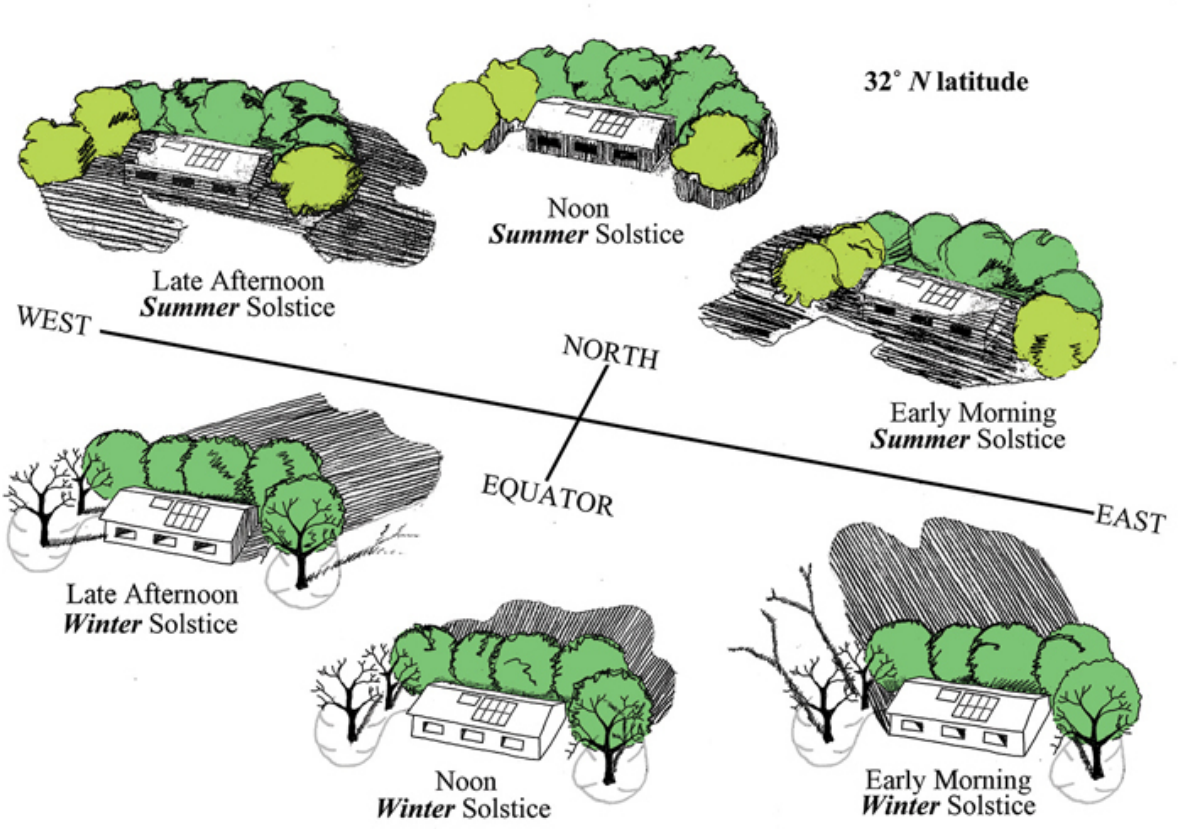


Fig. 1.8. Solar arc of trees and shrubs at 32° N latitude works with the changing angles of the sun's rays throughout the year. In summer, the arcs shade buildings, gathering areas, and gardens from rising and setting sun in summer, cooling temperatures by up to 20°F (11°C). In winter, when the sun is lower in the Equator-side of the sky, the arc retains full exposure to the winter sun for maximum free solar heating, solar power, and daylight during the cold months. Properly sized roof overhangs or window awnings shade south-/equator-side windows in summer, while letting in winter sun (see Volume 1, 3rd Edition, chapter 4 for sizing calculations and tips). And it really gets dynamic when the arc is set up to be passively irrigated by the runoff (and greywater if available) from the building or gathering area it shelters! See the planting section of chapter 2 for more details. Note: In the southern hemisphere, trees would be planted on the south rather than the north side of building.

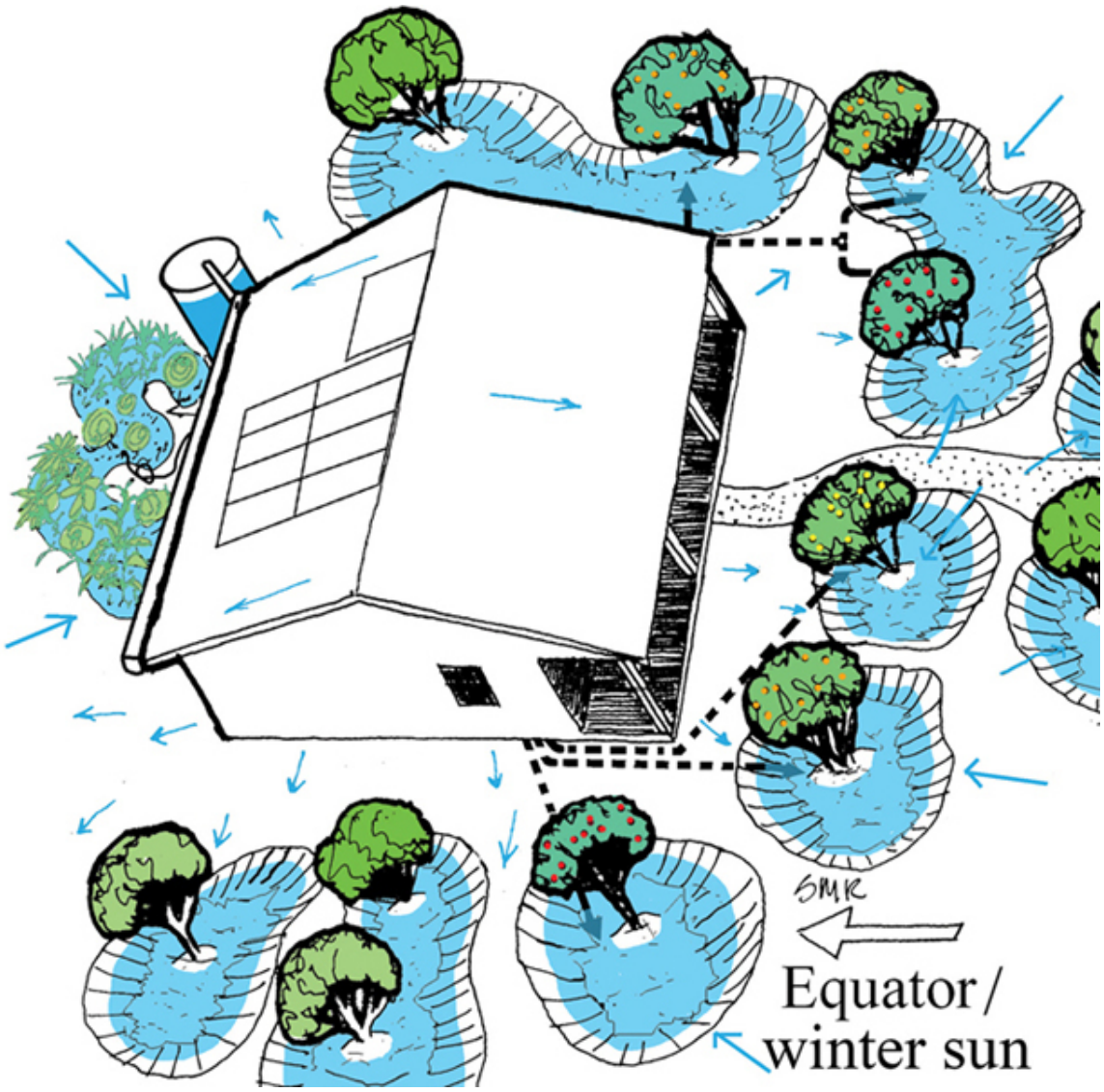


Fig. 1.9. Infiltration basins and new plantings within the wetter oasis zone 30 to 50 feet (9 to 15 m) from house, though at least 10 feet (3 m) from the building's foundation. Newly planted shade trees on the east, west, and north sides of a home in the northern hemisphere are irrigated with harvested runoff from roof and surrounding landscape, along with household greywater (distributed with below-ground pipe—see dotted lines). Low-growing garden is planted in basin on south-/equator-facing, or winter-sun side of home. Plantings within and beside basins will create a solar arc as they grow to mature size, shading and cooling building from rising and setting sun in summer, while letting in free winter sunlight and heat from winter sun/equator side, and maintaining solar exposure to solar panels and solar water heater on roof. Winter-deciduous trees on the east and west side of home let in even more winter light and heat. In fire-prone area, vegetation can be placed farther from home, while still within the oasis zone, and should be pruned up to prevent low

ground fires from migrating up low-growing branches. See chapter 2, fig. 2.4B, for a view of the arc's vegetation at mature size.

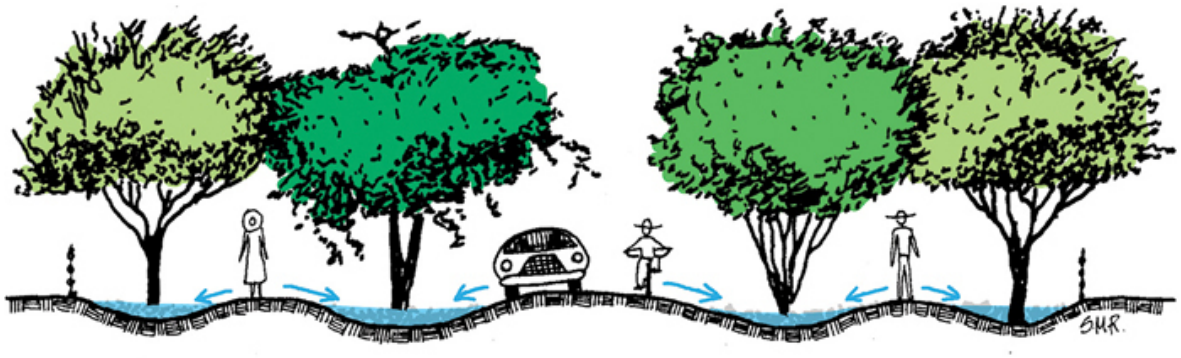


Fig. 1.10. Runoff from raised pathways and road drains to adjoining water-harvesting basins that are well mulched and vegetated to create living sponges within the drier oasis zones.

5. BEGIN HARVESTING WATER WITHIN YOUR SITE'S OASIS ZONES TO MAXIMIZE CONVENIENT, CONCENTRATED ABUNDANCE, WHILE REDUCING WASTEFUL, SPRAWLING RESOURCE CONSUMPTION.

Where you capture run*on* you've got it going *on*! While following the water-harvesting principles, focus much of your initial earthworks and plantings where convenience, efficiency, and your chances of success are the greatest, i.e., in the oasis zones. Oasis zones are the areas of your site with both conveniently accessible on-site water (rainfall, runoff or runon, and potentially cistern water and household greywater as well) *plus* intense human use (where you have the greatest impact and spend the greatest amount of time outdoors).

The *primary*, or *wetter, oasis zone* is usually within 30 to 50 feet (9 to 15 m) of homes and buildings—the area where roof runoff, household greywater, and people can be most efficiently engaged to support plantings. As this is the wetter oasis zone, it typically contains the more water-needy vegetation on the site, and often the *only* more water-needy vegetation on the site. Earthworks themselves should typically not be constructed within 10 feet (3 m) of a building because it is important to avoid saturating the soil beneath the foundation.

Secondary, *drier* oasis zones are areas within 10 to 20 feet (3 to 6 m) of frequently used paths, driveways, and roads. These lack greywater access, but they have human presence, and runoff from the adjoining accessway hardscape is easily captured.

These oasis zones characteristically suffer from the most human disturbance. Vegetation and topsoil are removed to build houses, patios, driveways and roads; soil is compacted by vehicle, foot, and pet traffic; and erosion occurs due to a lack of vegetation and mulch anchoring soil in place. Yet these areas can also benefit from the greatest available resources: the attention of you and other people; on-site harvestable water; and compost, prunings, and mulch from the house and yard. Use these resources to quickly and conveniently heal disturbances, to sustainably generate more on-site resources, and to reduce excessive maintenance. Follow the principle of *stacking functions* to create summer-cooling, and winter-heating shade trees arrayed in a solar arc; food-producing windbreaks; gardens; infiltration sponges; erosion control; bird and butterfly habitat; and beauty.

Concentrating your initial earthworks in areas with intense human attention is especially important in dryland environments where disturbed soil is naturally slow to revegetate and heal due to the lack of water. Constructing earthworks disturbs the soil and creates a temporary wound on the bare earth. Design these "wounds" so that they speed their own healing by harvesting water, soil, seeds, and fertility. Over time these earthworks enhance the land's ability to sustain more life. Nonetheless, any such abrasion is prone to erosion until stabilized with vegetation. Water-harvesting earthworks located in the broad landscape can remain bare for years if they happen to be created at the beginning of a drought cycle, especially if they do not receive mulch, supplemental water, and human care to jump-start the revegetation process.

Starting your initial work in the oasis zone also reins you in, keeps you from spreading yourself too thin by doing too much too fast, and reduces "backyard sprawl"—haphazardly starting projects throughout a site without efficiently and thoughtfully integrating them with one another. Focusing first on the wetter oasis zone, then the drier oasis zone(s) encourages steady growth that radiates out from a stable core, like lichen radiating out from its center. Your home and wetter oasis zone form your site's nuclei. Your water-harvesting efforts should radiate out as your experience, learning, and thoughtful integration of on-site resources (rainwater, greywater, winter sun, vegetation) grow to sustainably meet on-site needs (water, shelter, food, aesthetics) (figs. 1.11, 1.12).

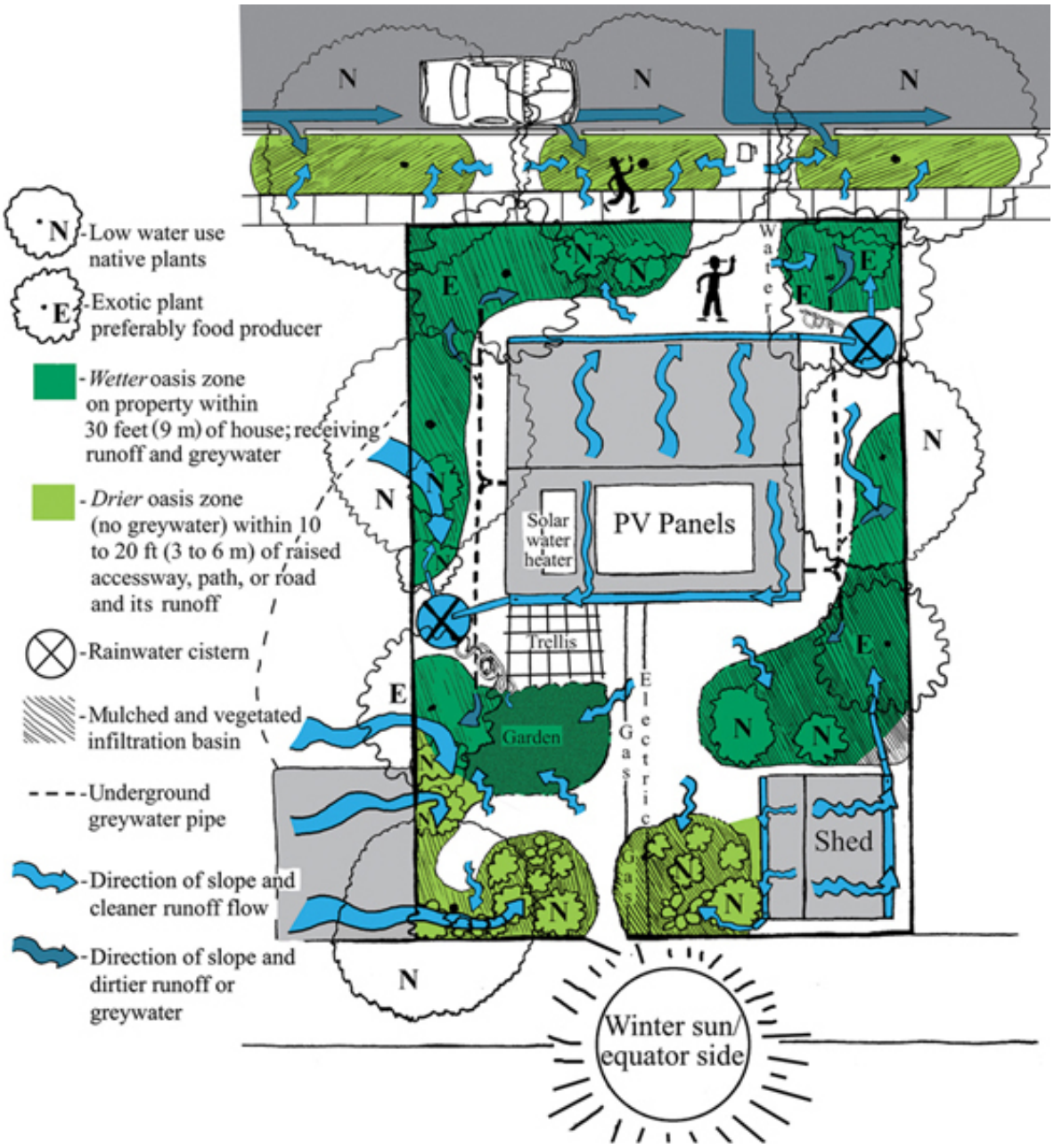

N
-Low water use native plants
E
-Exotic plant preferably food producer
-Wetter oasis zone on property within 30 feet (9 m) of house; receiving runoff and greywater
-Drier oasis zone (no greywater) within 10 to 20 ft (3 to 6 m) of raised accessway, path, or road and its runoff
-Rainwater cistern
-Mulched and vegetated infiltration basin
-Underground greywater pipe
-Direction of slope and cleaner runoff flow
-Direction of slope and dirtier runoff or greywater
Water
Solar water heater
PV Panels
Trellis
Garden
Gas
Electric
Shed
Winter sun/ equator side

Fig. 1.11. Integrated rainwater- and greywater-harvesting landscape site plan for an urban lot (plan view). Higher water-use plants (typically exotic fruit trees or larger native plants) are planted inside the wetter oasis zone, receiving roof and hardscape runoff and household greywater. Here vegetation passively shades and cools the home and people in summer mornings and afternoons, produces food, gives beauty, and provides other benefits. Only lower water-use plants—ideally natives—are planted beyond the wetter oasis zone. Compare to the similar figure in Volume 1, chapter 4, to see how this site's integrated design works with the resources and challenges of sun, noise, wind, neighbors, and more.

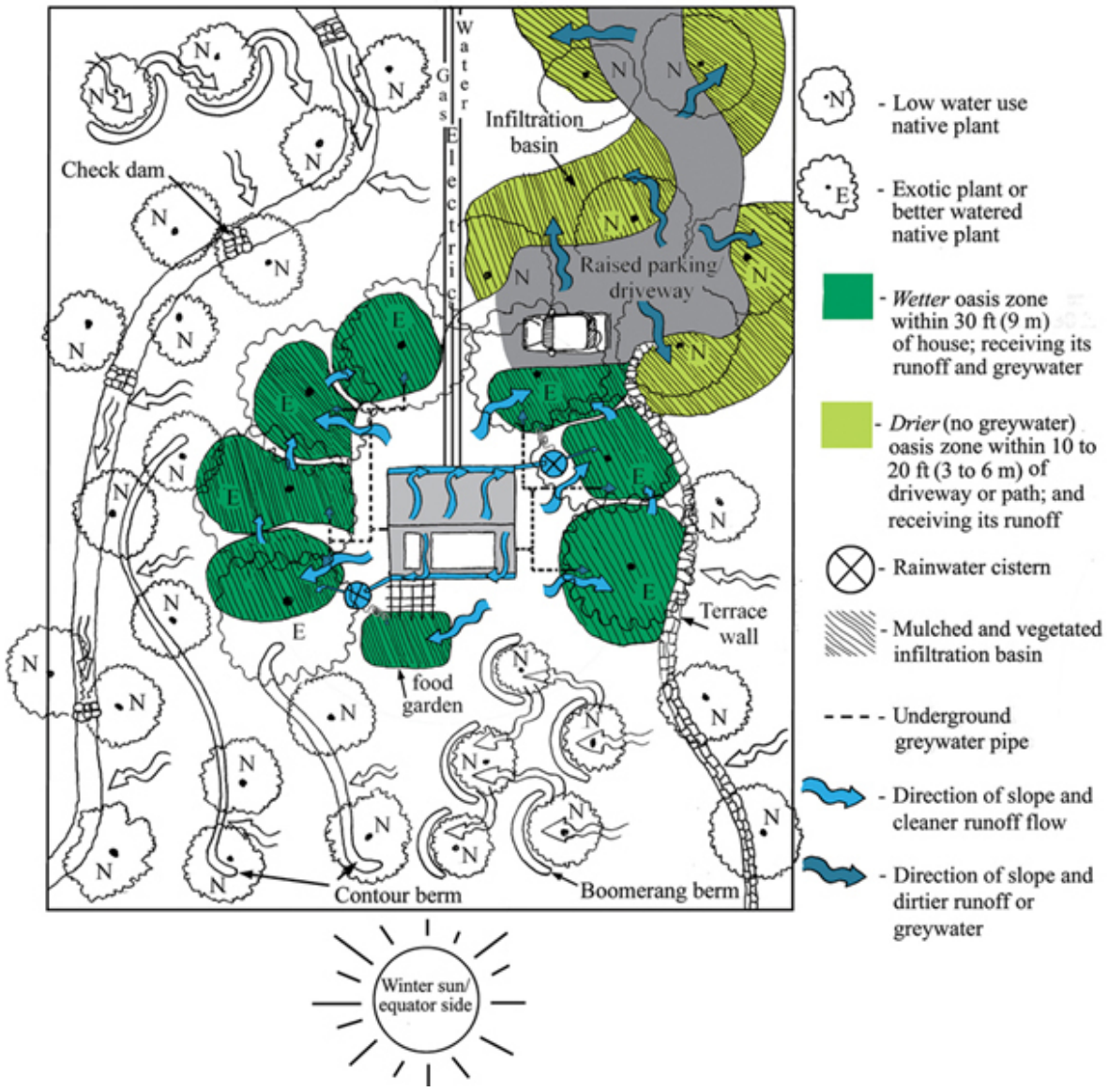

Water
Gas
Electric
Infiltration basin
Check dam
Raised parking/ driveway
Terrace wall
food garden
Contour berm
Boomerang berm
Winter sun/ equator side
- Low water use native plant
- Exotic plant or better watered native plant
- Wetter oasis zone within 30 ft (9 m) of house; receiving its runoff and greywater
- Drier (no greywater) oasis zone within 10 to 20 ft (3 to 6 m) of driveway or path; and receiving its runoff
- Rainwater cistern
- Mulched and vegetated infiltration basin
- Underground greywater pipe
- Direction of slope and cleaner runoff flow
- Direction of slope and dirtier runoff or greywater

Fig 1.12. Integrated rainwater- and greywater-harvesting landscape site plan for a suburban or rural lot (plan view). As in fig. 1.11, higher water-use plants (typically exotic fruit trees or larger native plants) are planted exclusively within or beside mulched basins or other earthworks inside the wetter oasis zone receiving roof runoff and greywater. A secondary drier oasis zone, lacking greywater, enhances the growth of lower water-use vegetation planted within 10 to 20 feet (3 to 6 m) of the raised driveway's hardscape and within reach of its runoff. Only low-water-use plants—ideally natives—are planted beyond the oasis zones. Better yet, leave existing native plants in place. A lower maintenance landscape might consist entirely of low-water-use natives.

6. CONSTRUCT INITIAL EARTHWORKS IN DISTURBED AREAS, NOT HEALTHY, INTACT ECOSYSTEMS.

When possible, build earthworks just after adjacent buildings and hardscapes are built or before new landscapes are planted. This will not result in any additional disturbance, and the newly created landforms will help heal the land more quickly and reduce the need for resource inputs and long-term maintenance. If you are retrofitting an existing landscape with water-harvesting earthworks, be careful to minimize damage to existing vegetation during implementation.

7. INVESTIGATE YOUR AREA'S INDIGENOUS, HISTORICAL, AND CONTEMPORARY WATER-HARVESTING STRATEGIES TO SEE WHAT HAS PROVEN TO WORK IN YOUR CLIMATE AND CONDITIONS.

This research will expose you to previous successes and failures, and give you ideas about what is possible and what is successful. You can also research water-harvesting traditions and practices in other areas of the world with climates similar to that of your site. Search water-harvesting literature, the Internet, the press, and local permaculture and water-harvesting organizations. See appendix 4 for a list of water-harvesting resources.

8. MAKE EARTHWORK BASINS DEEPER AND BERMS BIGGER THAN YOU MIGHT INITIALLY THINK NECESSARY.

Over time, basins fill with sediment and organic matter, and berms erode. Making basins deeper and berms bigger initially will increase their lifespan, effectiveness, and capacity. Specific details on earthwork sizing and erosion prevention are provided in respective earthwork technique chapters later in this volume.

9. PAY SPECIAL ATTENTION TO THREE IMPORTANT ELEVATIONS AS YOU CREATE YOUR EARTHWORKS: THE SPILLWAY, THE SURROUNDING LAND AREA, AND THE BOTTOM OF THE BASIN.

Elevation 1 – Make sure the bottom of the earthwork or its basin is sufficiently lower than the elevation of the spillway to ensure the earthwork holds water rather than draining it all through the spillway (fig. 1.13).

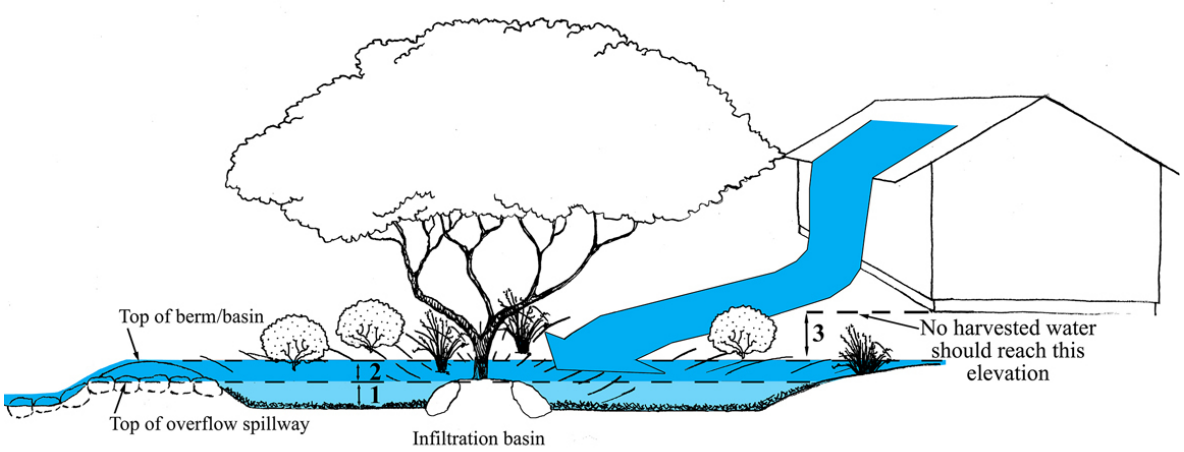


Fig. 1.13. Three important elevations: Elevation 1: Earthwork bottom or basin is lower than elevation of spillway to ensure water is harvested, rather than drained. Elevation 2: Overflow spillway is the low point of earthwork's perimeter. Elevation 3: Perimeter or edge of earthwork is below anything you don't want water to back up against or flood.

Elevation 2 – Make sure the earthwork's overflow spillway is truly the low point of the earthwork's perimeter or edge. This is important for guaranteeing that the overflow spillway, and not another inadvertently low point, acts as the overflow point.

Elevation 3 – Make sure the perimeter or edge of the earthwork is low enough in relation to the elevation of the surrounding area so if the spillway gets clogged harvested water will not back up against or flood anything you don't want flooded.

The *minimum* elevation difference between each of these three points should be 4 inches (10 cm), but a larger difference is typically much prefered. See appendix 1 for information and tools on how to measure these points.

10. MAKE SURE YOUR EARTHWORKS PERCOLATE OR INFILTRATE WATER.

Do not create mosquito-breeding puddles! Make sure water does not stand for more than 12 hours. Mulching and planting earthworks is typically the best remedy for addressing long-standing water. The more roots and burrowing soil life you have, the more quickly water will infiltrate. Dropping the level of overflow spillways can also help by releasing water that can't infiltrate quickly. Chapter 12 gives you more strategies for infiltrating water fast, and shows you a way to test the percolation rate of your soils. The next tip will also help you promote infiltration.

11. DIVIDE LARGE WATERSHEDS INTO SMALLER SUBWATERSHEDS.

Conventional stormwater management designs typically place a large detention/retention basin at the bottom of a site to accept all the runoff from the site's watershed. These basins hold so much water in big storms that the vegetation in them drowns while the rest of the site is drained and dehydrated (fig. 1.14A).

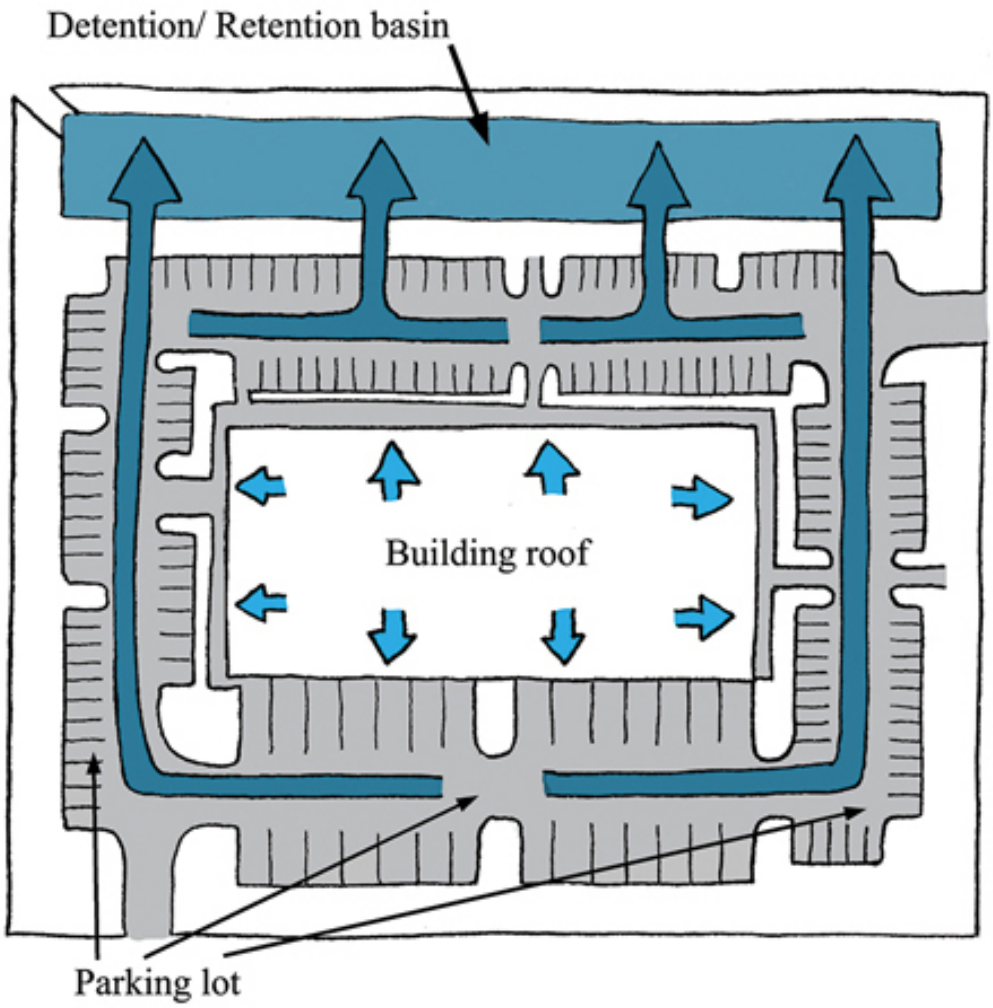


Fig. 1.14A. Runoff from commercial/industrial site's entire watershed is directed to *one* flooded detention/retention basin at site's lowest elevation. This concentrated water turns into a problem, while leaving the rest of the site drained and dehydrated. Arrows denote water flow. Compare to fig. 1.14B.

I advocate collecting site runoff at multiple points throughout the site's watershed, starting at the top and continuing all the way to the bottom. This

divides the site watershed into multiple smaller subwatersheds, each with its own water-harvesting earthwork(s). Each subwatershed yields an easily managed volume of harvested water that quickly infiltrates to passively irrigate associated plantings. In addition, this multi-subwatershed water-harvesting approach controls flooding and hydrates the entire site. Fig. 1.14B illustrates this approach for a commercial development. The Real-Life Examples section of chapter 2 shows how this was done for a 28-unit cohousing development. Chapter 8 shows examples along streets and public rights-of-way, and within parking lots. Chapter 12 has examples for single-family residences, urban and rural.

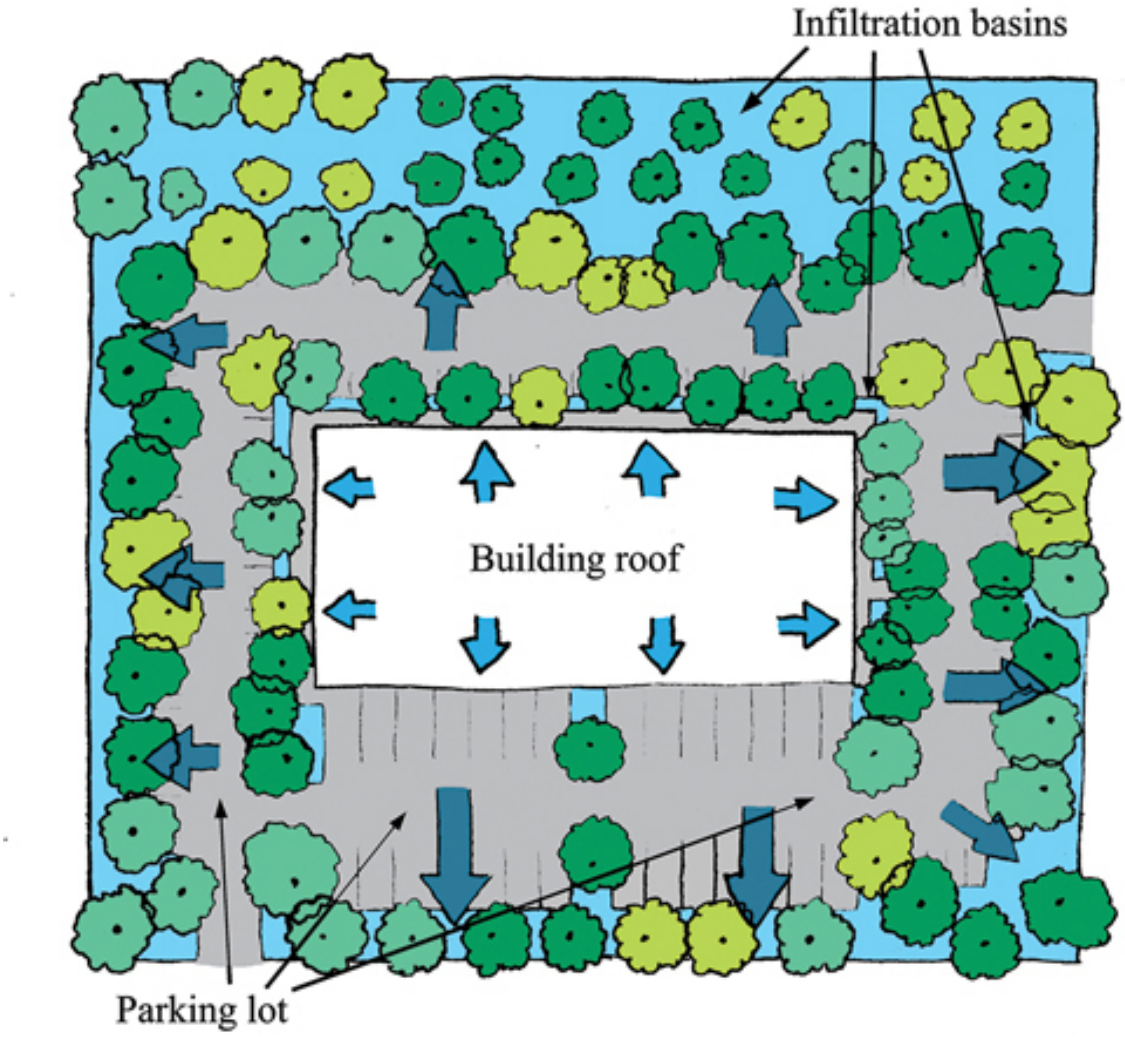


Fig. 1.14B. Site runoff is directed to *multiple* water-harvesting infiltration basins, dividing the site watershed into multiple subwatersheds. All water quickly infiltrates to passively irrigate landscape and grow native shade trees in mulched basins. These trees act as living air conditioners, living carports, and living water and air filters. Spreading out harvested water spreads the resource

around to hydrate more of the site and generate more on-site resources. The retention basin size at bottom of site can be greatly reduced or eliminated; furthermore, more beneficial vegetation can be grown within it due to lower, more easily managed water volumes. Compare to fig. 1.14A.

If after dividing a site into smaller subwatersheds you still have too much water collecting within an area or earthwork (fig. 1.15A), consider dividing the contributing watershed up even more. Installing more earthworks, cisterns, and/or plantings above the inundated area will reduce the volume of contributing runoff, while further increasing a more expansive slowing, spreading, and sinking of water throughout its watershed (fig. 1.15B).

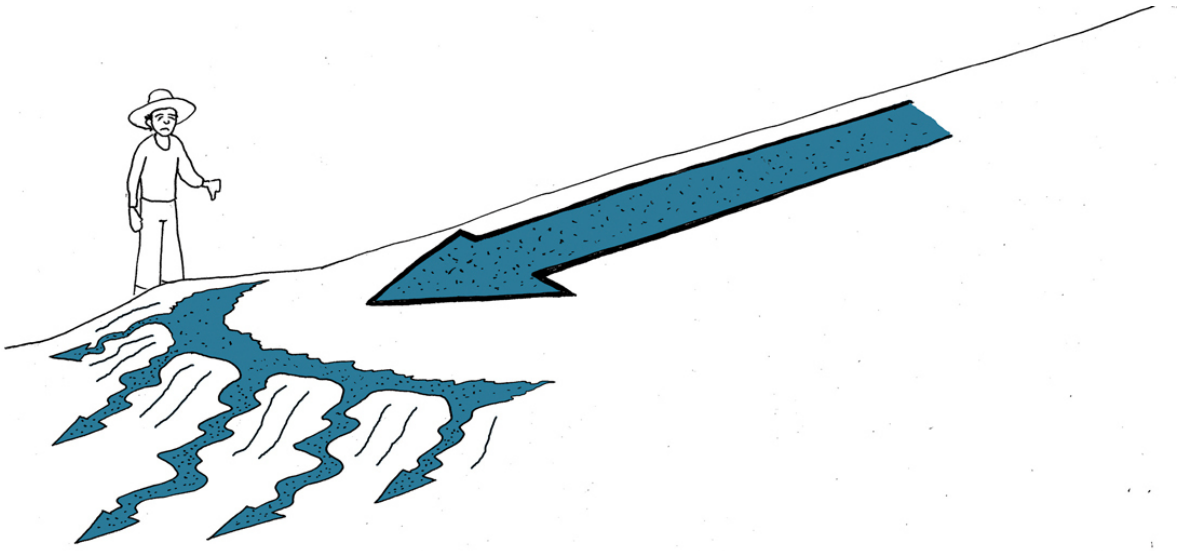


Fig. 1.15A. Too much runoff contributing to, inundating, and then eroding, a water-harvesting earthwork.

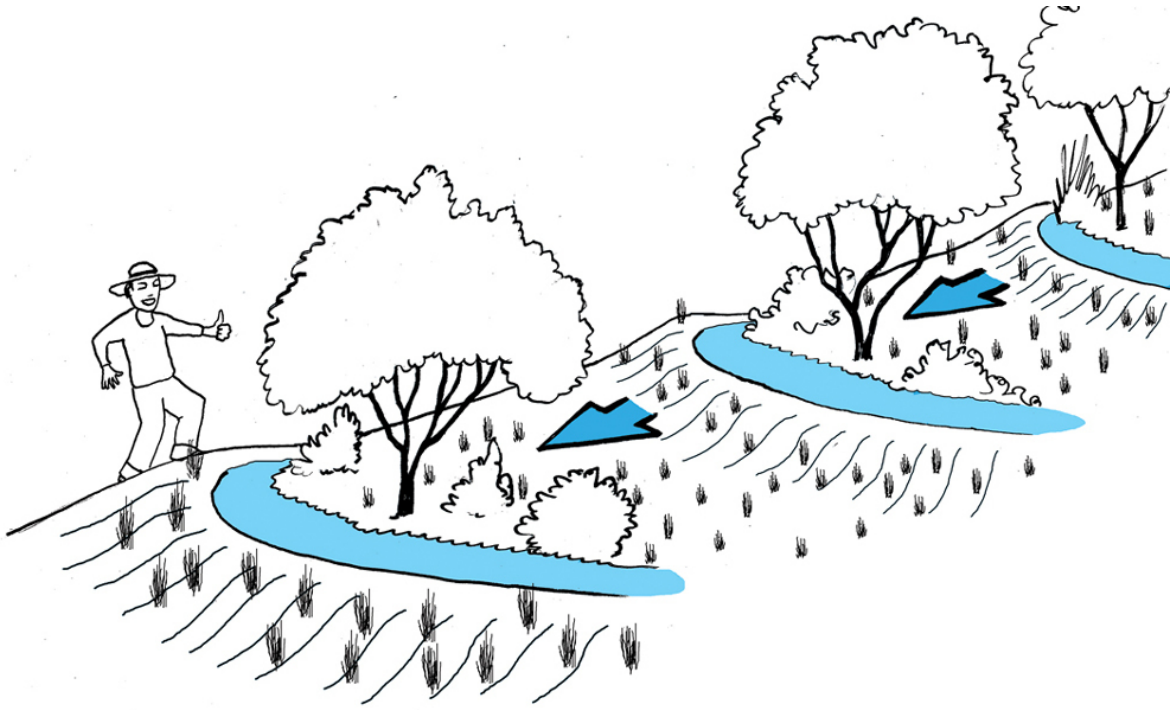


Fig. 1.15B. More runoff turned into soak-in higher in the watershed with more earthworks and vegetation, so all structures work well and none are inundated.

12. DIRECT DOWNSPOUTS, CISTERNS, AND GREYWATER DRAINS TO HIGH POINTS AT THE SITE SO GRAVITY CAN BE USED TO DISTRIBUTE WATER THROUGHOUT THE SITE VIA A SERIES OF EARTHWORKS.

See fig. 1.16.

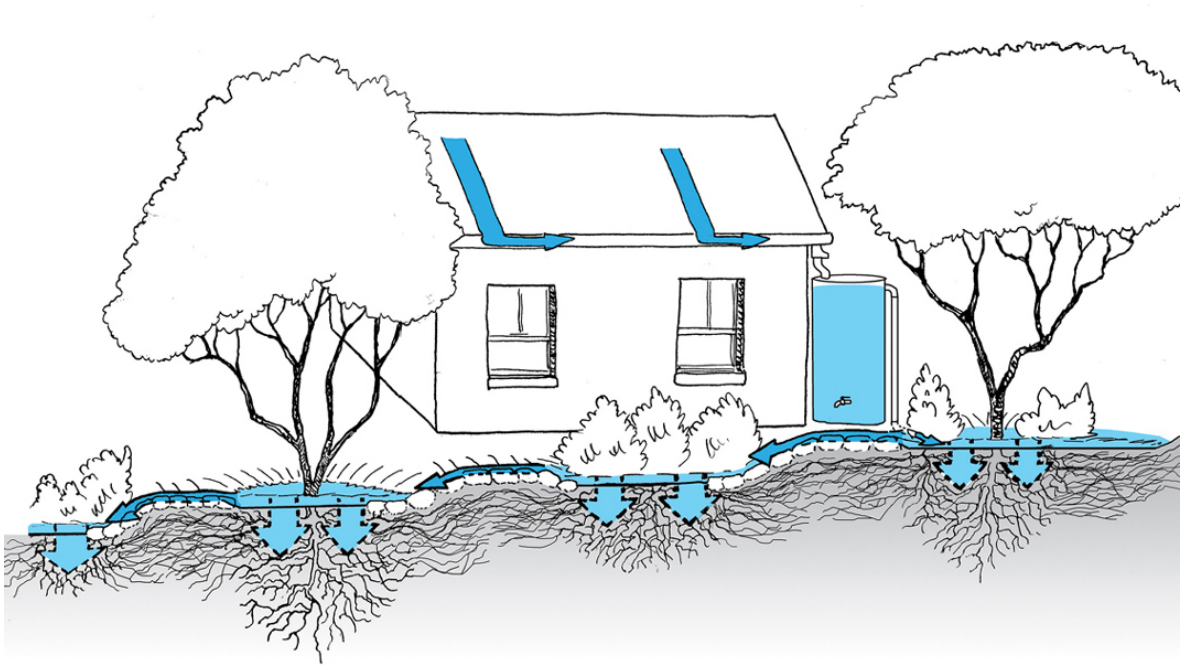


Fig. 1.16. Downspout directing water to a high point at the site to passively spread and infiltrate water over more of the site. Water from cistern faucet and overflow pipe is gravity-distributed to all areas downslope. Note: Terraced basins are at least 10 feet (3 m) from building foundation.

13. HARVEST WATER THROUGHOUT A WATERSHED BEFORE HARVESTING WATER WITHIN THE WATERCOURSE THAT DRAINS IT.

Often people are mesmerized by the amount of water flowing down their site's watercourses—the site's natural ephemeral or perennial drainageways— and they want to harvest that water first. But remember the second water-harvesting principle: *Start at the top (high point) of your watershed and work down* to make work easier and more efficient while hydrating the whole site, not just the bottom.

14. DO NOT CUT OFF AN EXISTING, HEALTHY, NATURAL WATERCOURSE.

Natural watercourses are important wildlife habitats and corridors that should be maintained. While you can harvest water above a natural watercourse, do not cut off all water flow to the watercourse. Direct overflow from earthworks above to natural drainages below to keep existing, erosion-controlling vegetation in the watercourse healthy while managing surplus water.

15. UTILIZE OVERLAND FLOW OF WATER, RATHER THAN PIPED FLOW.

I advocate using pipes to direct relatively clean water from rooftops, downspouts, cisterns, or household greywater systems to earthworks. But once water has flowed over a paved or earthen surface, it is best to continue the flow of the water using earthworks rather than pipes (figs. 1.17A, B).

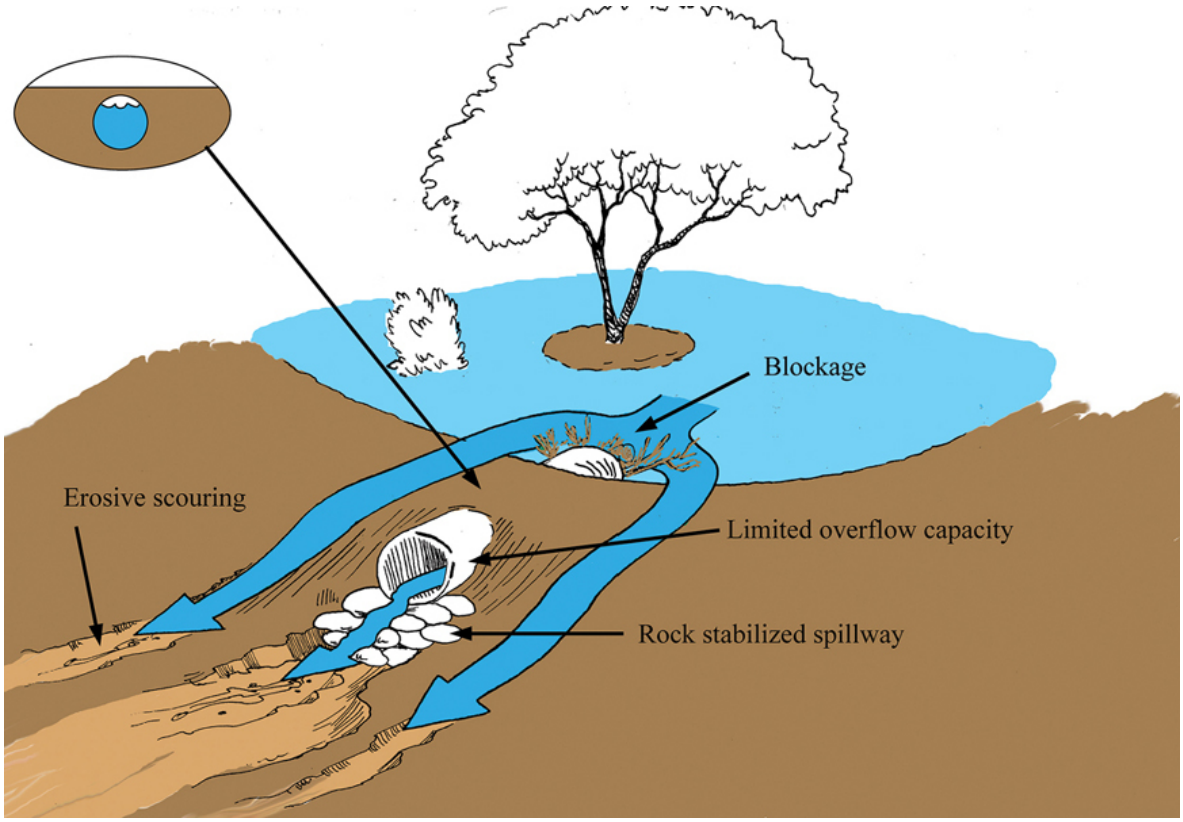


Fig. 1.17A. Overflow piped from one basin to another. The pipe has a limited flow capacity and is likely to clog with debris on the inlet end, while concentrating water into a more erosive force on the outlet end. Oval shows cross section of water flow through pipe.

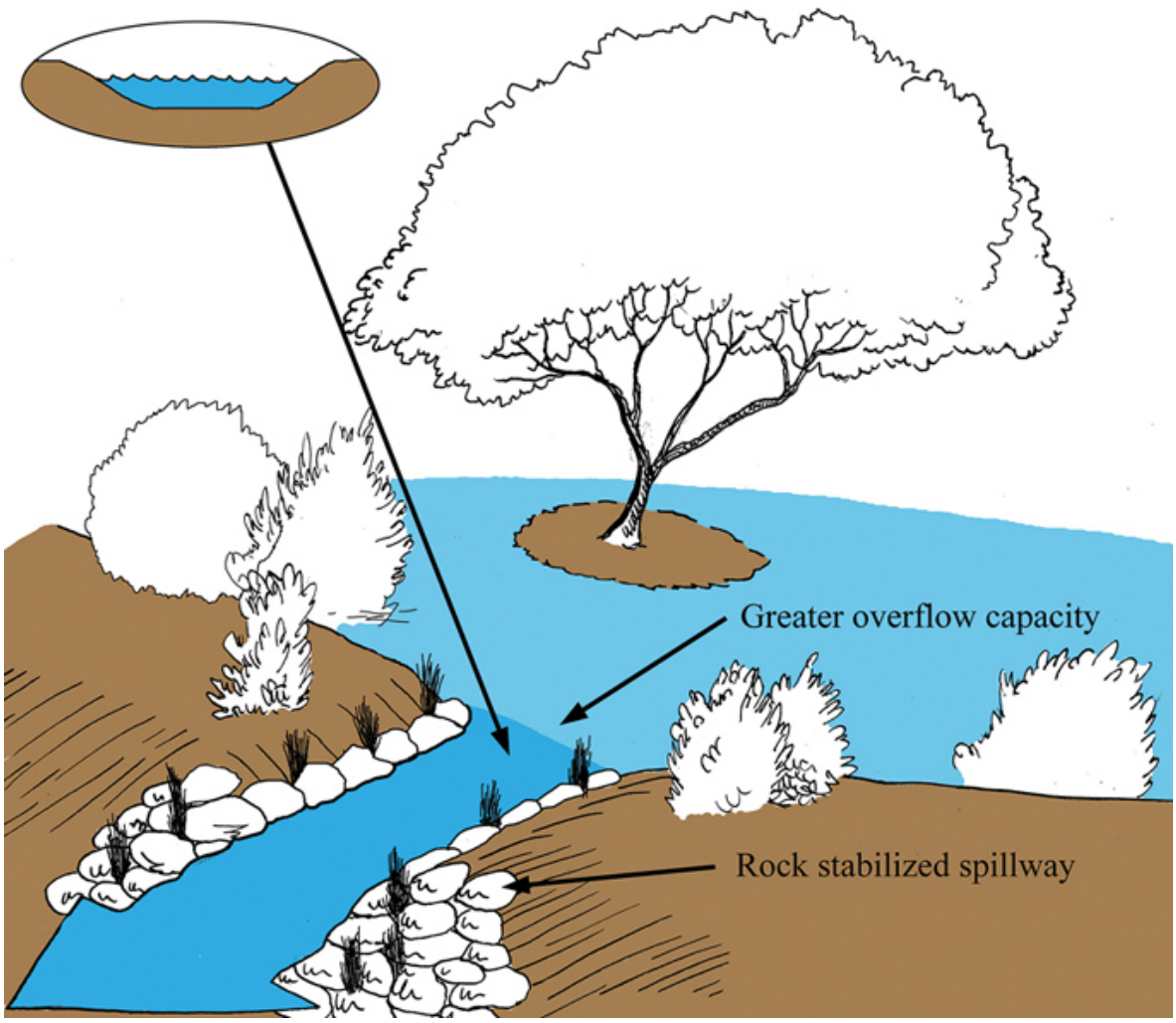


Fig. 1.17B. An overland diversion swale overflows from one basin to another. The swale has a greater flow capacity than a pipe and it increases as more water moves through it and rises to the widening upper banks. It is unlikely to clog due to the larger area, and because debris can flow with the water without obstruction. The swale also concentrates the outflow less than a pipe so the potential for downstream erosion is less. Oval shows cross section of water flow through diversion swale.

Pipes can clog with dirt, debris, roots, and critters. They cost money. And they concentrate water, increasing its erosive force as it exits the pipe. Directing water overland via depressions, spillways, diversion swales, and natural watercourses eliminates the maintenance needs of piping. There is nothing to buy. And overland strategies slow, spread, and infiltrate water flow more easily.

16. DO *NOT* IMPORT DIRT ONTO, OR EXPORT DIRT OFF, A SITE UNTIL YOU'VE EXHAUSTED YOUR EXISTING ON-SITE

RESOURCES AND NEEDS.

To save time, money, and the inconvenience of transporting dirt, get the dirt you need to raise a path or construct berms by digging new infiltration basins or enlarging existing basins on site. If you need to get rid of surplus soil, raise the elevation of building pads, patios, and driveways or construct earthen adobe, rammed earth, or cob walls, benches, or other structures. Once you've exhausted on-site opportunities, collaborate with neighbors.

If you have good topsoil where you are excavating your earthworks, put that topsoil to the side while excavating. And when your earthworks are done, place the fertile, porous topsoil back atop the less fertile, less porous subsoil you've exposed to better regenerate and revegetate the disturbed area. (Dig your earthworks deep enough to take into account how much that topsoil will fill in your excavations without taking away the desired capacity of your earthworks).

17. IN NEW CONSTRUCTION, RUN ALL UNDERGROUND UTILITY LINES (GAS, WATER, ELECTRIC, CABLE, PHONE, MAIN DRIP IRRIGATION PIPE) UNDER RAISED PATHWAYS OR ACCESS WAYS, NOT BENEATH YOUR EARTHWORKS.

Using this strategy, you will always know where the utility lines are, and they will always be accessible. In addition, roots are less likely to disturb the utility lines and you won't need to disrupt plants to access the lines.

18. FOCUS EARTHWORKS AND PLANTINGS AROUND THE PERIPHERY OF YOUR YARDS.

Make your small yards feel big, not claustrophobic. Basins and plants placed in the middle of a small yard fill it up. Basins, shrubs, and trees placed on the yard's periphery leave nice open space in the center while softening and masking boundary fences and walls (fig. 1.18). Peripheral trees cast shade over much of the yard, but their trunks are out of the way.

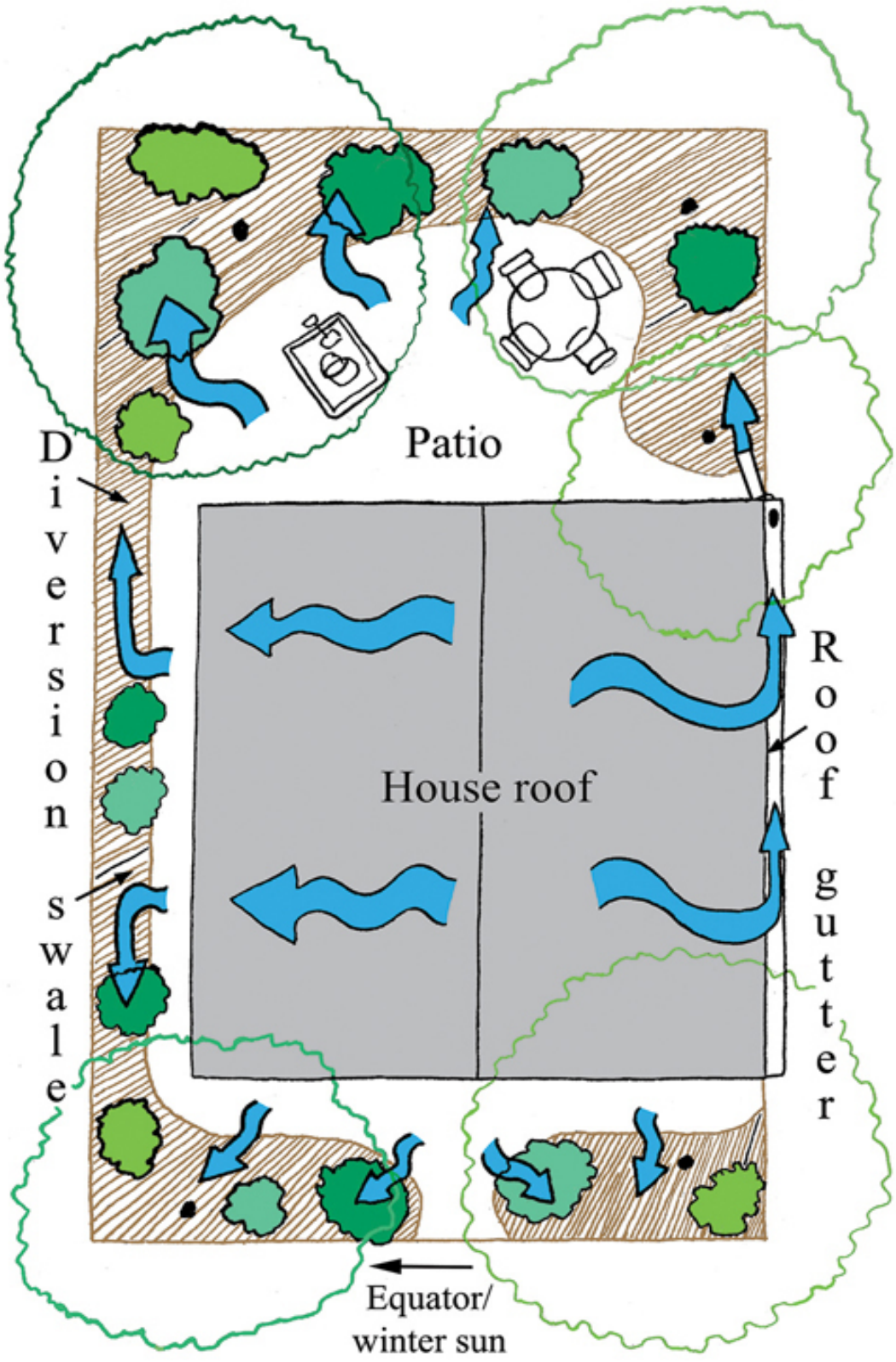

Patio
Diversion swale
House roof
Roof gutter
Equator/
winter sun

Fig. 1.18. Water-harvesting earthworks and plantings are emphasized on the periphery of small (or even big) yards to shelter them, while making them feel bigger. Diversion swale in narrow side yard infiltrates water for plantings, while directing overflow to larger earthworks in front and back yards. Trees shade out summer rising and setting sun, while low-growing plants let in winter sun and light on the south side of this northern hemisphere home. See Volume 1, chapter 4, for more on passive-solar landscape design.

19. DRAIN WATER FROM NARROW SIDE YARDS USING GRADUALLY SLOPED DIVERSION SWALES.

Very gradually sloped diversion swales placed along the property line will allow some water infiltration in the side yard to irrigate perimeter plantings while moving surplus water away to prevent soil saturation against the house. Design the diversion swales to route surplus runoff to larger front and back yards where water can infiltrate in multiple earthworks to support plantings (fig. 1.18).

20. DRAIN WATER AWAY FROM BUILDINGS SET LOW IN THE LANDSCAPE BY RE-GRADING THE LAND AROUND THEM.

If runoff water flows toward your home (fig. 1.19A), regrade the land slope around the building so water flows away and fills earthworks set 10 feet (3 m) or more from the foundation. When regrading, make sure any soil in contact with the building is at least 4 to 6 inches (10 to 15 cm) below the top of the foundation or stem wall to prevent moisture and/or termites in the soil from making contact with your walls, where they might cause damage (see fig. 1.19B). In addition to regrading around the house, place earthworks high in the site's watershed to intercept water and create overflow routes that direct overflow from these earthworks away from the building.

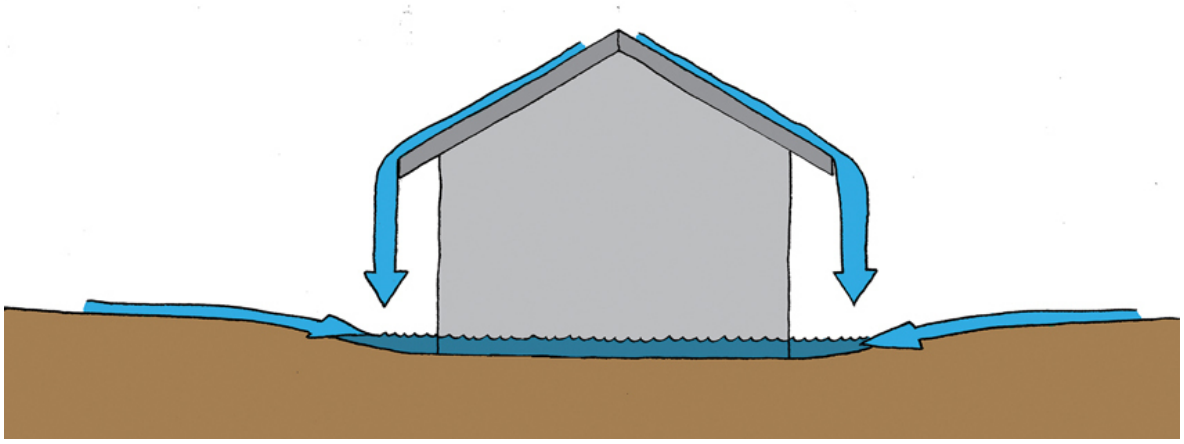


Fig. 1.19A. A house set low in the landscape and prone to flooding.

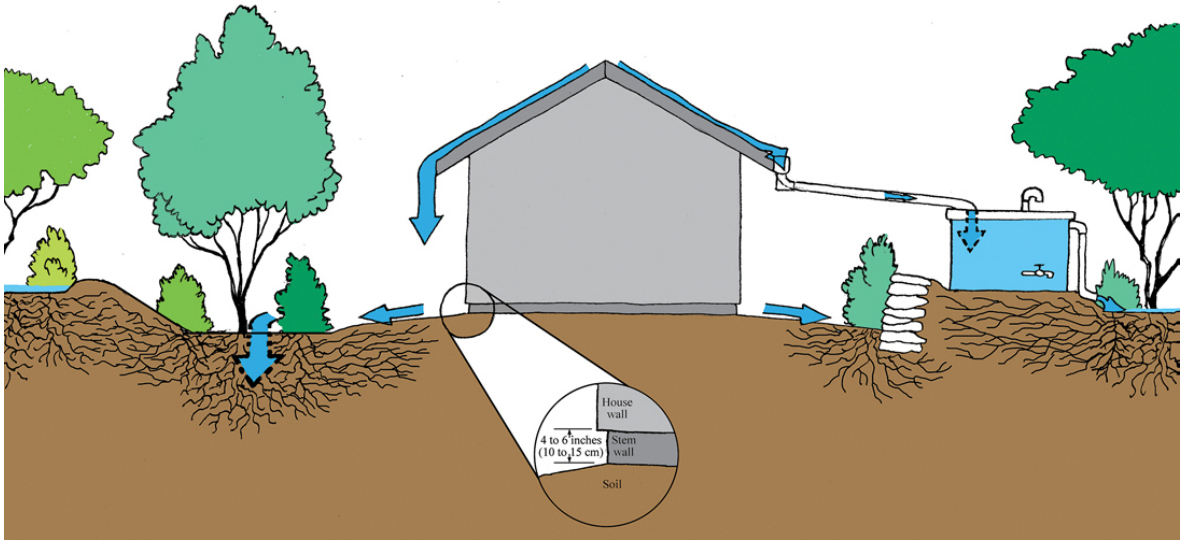


Fig. 1.19B. Landscape regraded to drain and harvest water away from the house to eliminate flooding and passively irrigate the vegetation. Note: A space between the top of the building's stem wall and the wall of the house is kept free of soil to prevent moisture and subterranean termites from entering the wall.

21. UTILIZE NATIVE VEGETATION WITHIN YOUR LANDSCAPES.

The easiest way to create a water-sustainable landscape is to leave all existing native vegetation in place. It is already established, and can survive on rainfall alone.

The next easiest way is to revegetate a site exclusively with native vegetation. Ideally use low-water-use indigenous plants typically found within a 25-mile (40-km) radius of the site and 500 feet (150 m) above or below the site's elevation. Though some sites may require using native species from farther away to bring in more diversity, start with species within a small radius to ensure you do not overlook superior local species. Native vegetation is typically the most beneficial for native wildlife and creates a "sense of place," rooting us to the local bioregion. Having evolved over millennia within the local climate, soils, and natural rainfall regimes, these plants are very well adapted to your site. Plant natives within or beside water-harvesting earthworks and they'll *thrive*.

22. LIMIT EXOTIC PLANTS TO THE OASIS ZONE.

Exotic vegetation such as fruit trees and vegetables typically need more water and care than plants native to your site's drier microclimates. If used, plant these exotics exclusively in the oasis zone where runoff and greywater are readily available and can meet their higher water needs. You will also be there to provide additional attention and harvest the bounty. Plant tough drought-tolerant natives in earthworks beyond the oasis zone, where they can thrive on rainfall alone once established, while creating a shelter belt that protects the tender exotics from excess sun and wind. However, keep in mind that not all natives are equal. Those naturally found in wetter areas are more water-needy, while those found in drier areas are more drought-tolerant. Plant accordingly, depending on site needs and water availability. Chapter 11 expands on this.

23. TO DETERMINE WHAT PLANTS TO PLACE WITHIN OR BESIDE YOUR EARTHWORKS, TAKE A HIKE!

Go into nearby wild natural areas with elevation, microclimate, and rainfall similar to your site, and see what grows naturally in depressions or along ephemeral waterways. These are the plants that will grow well within the basins of your earthworks. Observe the plants that grow naturally in higher, well-drained areas. Place these plant species atop berms or beside earthwork basins, but not in the basins. Mimic nature.

For placement of fruit trees and other exotic species, read plant books and ask knowledgeable plant nursery staff about what such trees require. If they need good drainage, plant them beside, not within, earthworks so their roots can access harvested water but their root crowns remain high and well drained.

24. LIVE WITHIN YOUR SITE'S WATER BUDGET.

To truly turn water scarcity into abundance we must work to give the watershed more than we take from it. This goes beyond maintaining current degraded conditions; we need to improve them. Building earthworks and establishing vegetation to capture rainwater previously lost to runoff and evaporation is a primary way to improve conditions. But earthworks and plantings alone are not enough. We must make sure we don't overconsume or overspend the site's limited water budget. To achieve this goal I give you the following challenge:

Consume less water on site than falls on your site in an average year of rainfall.

Your total average annual on-site water consumption (domestic/interior and landscape/exterior) should be less than the total average annual rainfall at your site. You can estimate the income of your site's water budget by estimating how much rain falls on your site in an average year using the equations in boxes 1.3, 1.4 and the example illustration in fig. 1.20. Then estimate how much additional income or rainfall you gain through "runon" (i.e. runoff running *onto* the site), and how much income or rainfall you lose to runoff running off the site (box 1.4 and fig 1.21). Consult local climate records and your rain gauge for local rainfall.

Box 1.3. Calculating Rainfall Volumes

CALCULATING RAINFALL VOLUMES IN ENGLISH UNITS:

To calculate the volume of rainfall in cubic feet that falls in an average year on a specific catchment area, such as your roof, yard, section of street, neighborhood, or other subwatershed:

CATCHMENT AREA (in square feet)
multiplied by the AVERAGE ANNUAL RAINFALL (in feet)
equals the TOTAL RAINWATER FALLING ON THAT CATCHMENT
IN AN AVERAGE YEAR (in cubic feet)

(or)

CATCHMENT AREA (ft^2) × AVERAGE RAINFALL (ft) = TOTAL RAINWATER (ft^3)

If you normally measure annual rainfall in inches, simply divide inches of rain by 12 to get annual rainfall in feet. For example, folks in Phoenix, Arizona, get about 7 inches of annual rainfall, so they would divide 7 by 12 to get 0.58 feet of annual rain.

Once you get your answer in cubic feet of annual average rainfall, convert cubic feet to gallons by multiplying your cubic-foot figure by 7.48 gallons per cubic foot. The whole calculation looks like this:

CATCHMENT AREA (ft^2) × RAINFALL (ft) × 7.48 gal/ft^3 = TOTAL RAINWATER (gal)

For example, if you want to calculate how much rainwater in gallons falls on your 55-by-80-foot (4,400-square-foot) lot (fig. 1.20) in a normal year where annual rainfall averages 12

inches, the calculation would look like this:

4,400-square-foot catchment area × 1 foot of average annual rainfall × 7.48 gallons per cubic foot = 32,912 gallons of rain falling on the site in an average year

CALCULATING RAINFALL VOLUMES IN METRIC UNITS:

To calculate the volume of rainfall falling on a specific catchment area in liters:

CATCHMENT AREA (in square meters) × AVERAGE ANNUAL RAINFALL (in millimeters) = TOTAL RAINWATER FALLING ON A CATCHMENT AREA IN AN AVERAGE YEAR (in liters)

For example, if you want to calculate how much rainwater in liters falls on your 24-by-16.5-meter (396-square-meter) lot in a normal year where annual rainfall averages 304 millimeters, the calculation would look like this:

396-square-meter catchment area × 304 millimeters annual rainfall = 120,384 liters of rain falling on site in an average year

CALCULATING RAINFALL VOLUMES FOR A GIVEN RAIN EVENT IN ENGLISH *OR* METRIC UNITS:

To calculate the volume of rainfall on a specific catchment for a given rain event:

Use the calculations above, but enter the amount of "rainfall from a given rain" in place of "average annual rainfall."

Note: Appendix 2 provides more detailed information on conversions, constants, and calculations for water harvesting.

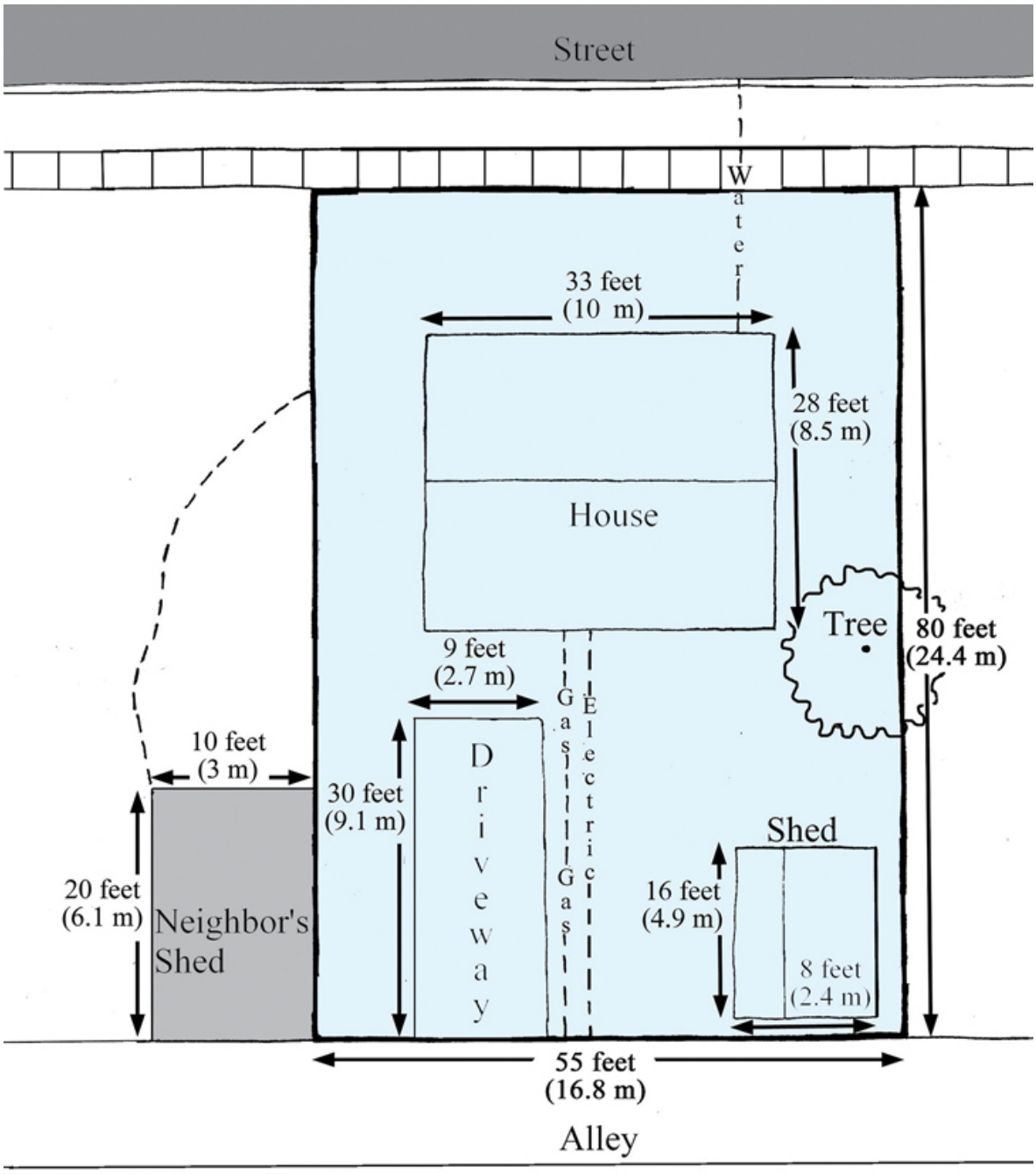


Fig. 1.20. Site map (overhead/plan view) of a 4,400-square-foot (409-m^2) property. In an average year of 12 inches (305 mm) of precipitation the site (in blue) receives 32,912 gallons (124,585 liters) of rainfall "income." See box 1.3 for how to calculate a site's rainfall "income." Compare to fig. 1.21.

Box 1.4. Calculating Runoff and Runon Volumes

You can get a ballpark estimate of runoff volume from any sloped surface by multiplying the volume of rain that falls on that surface by its "runoff coefficient"—the average

percentage of rainwater that runs off that type of surface. For example, a rooftop with a runoff coefficient of 0.95 estimates that 95% of the rain falling on that roof will run off.

The runoff coefficient for any given surface depends on what the surface is composed of. Rainfall intensity also affects the coefficient: the higher the rainfall intensity, the higher the runoff coefficient. Ranges and averages of various runoff coefficients I use in the southwest U.S. are as follows:

- A roof or impervious paving (such as concrete patio or an asphalt street): 0.80-0.95
- Sonoran Desert uplands (healthy indigenous landscape): range 0.20-0.70, average 0.30-0.50
- Bare earth: range 0.20-0.75, average 0.35-0.55
- Grass/lawn: range 0.05-0.35, average 0.10-0.25
- For gravel use the coefficient of the ground below the gravel.

The runoff coefficient for earthen surfaces is greatly influenced by soil type and vegetation density. Large-grained porous sandy soils tend to have lower runoff coefficients while fine-grained clayey soils allow less water to infiltrate and therefore have higher runoff coefficients. Whatever your soil type, the more vegetation the better, since plants enable more water to infiltrate the soil.

CALCULATING YARD RUNOFF/RUNON: AN EXAMPLE

CALCULATING RUNOFF/RUNON VOLUMES IN ENGLISH UNITS:

Let's say we are on a site receiving 18 inches of rain in an average year, and the neighbor has about a 25-by-12-foot bare section of his yard that drains onto our example property. The soil is clayey and compacted.

Determine the available rainwater running off that section of the neighbor's yard, and running on to our land by multiplying its catchment area (300 square feet) by the average annual rainfall in feet (1.5) by 7.48 (to convert the answer to gallons):

CATCHMENT AREA (ft^2) × RAINFALL (ft) × 7.48 gal/ft^3 = TOTAL RAINWATER (gal)

300 ft^2 × 1.5 ft × 7.48 gal/ft^3 = 3,366 gallons of rain falling on that section of the neighbor's yard in an average year.

Multiply that figure by the soil surface's runoff coefficient of 0.60:

3,366 gallons × 0.60 = 2,019 gallons annually running off the neighbor's compacted yard into ours. Add that to our site's annual rainwater budget.

CALCULATING RUNOFF/RUNON VOLUMES IN METRIC UNITS:

Let's say we are on a site receiving 457 mm of rain in an average year, and the neighbor has about a 7.5-m-by-3.6-m bare section of his yard that drains onto our example property. The soil is clayey and compacted.

Determine the available rainwater running off that section of the neighbor's yard and running on to our land by multiplying its catchment area (27 m^2) by the average annual rainfall in millimeters (457) to get liters of runoff in an average year of rain:

CATCHMENT AREA (m^2) × RAINFALL (mm) = TOTAL RAINWATER (liters)

27 m^2 × 457mm = 12,339 liters of rain falling on that section of the neighbor's yard in an average year.

Multiply that figure by the soil surface's runoff coefficient of 0.60:

12,339 liters × 0.60 = 7,403 liters annually running off the neighbor's compacted yard into ours. Add that to our site's annual rainwater budget.

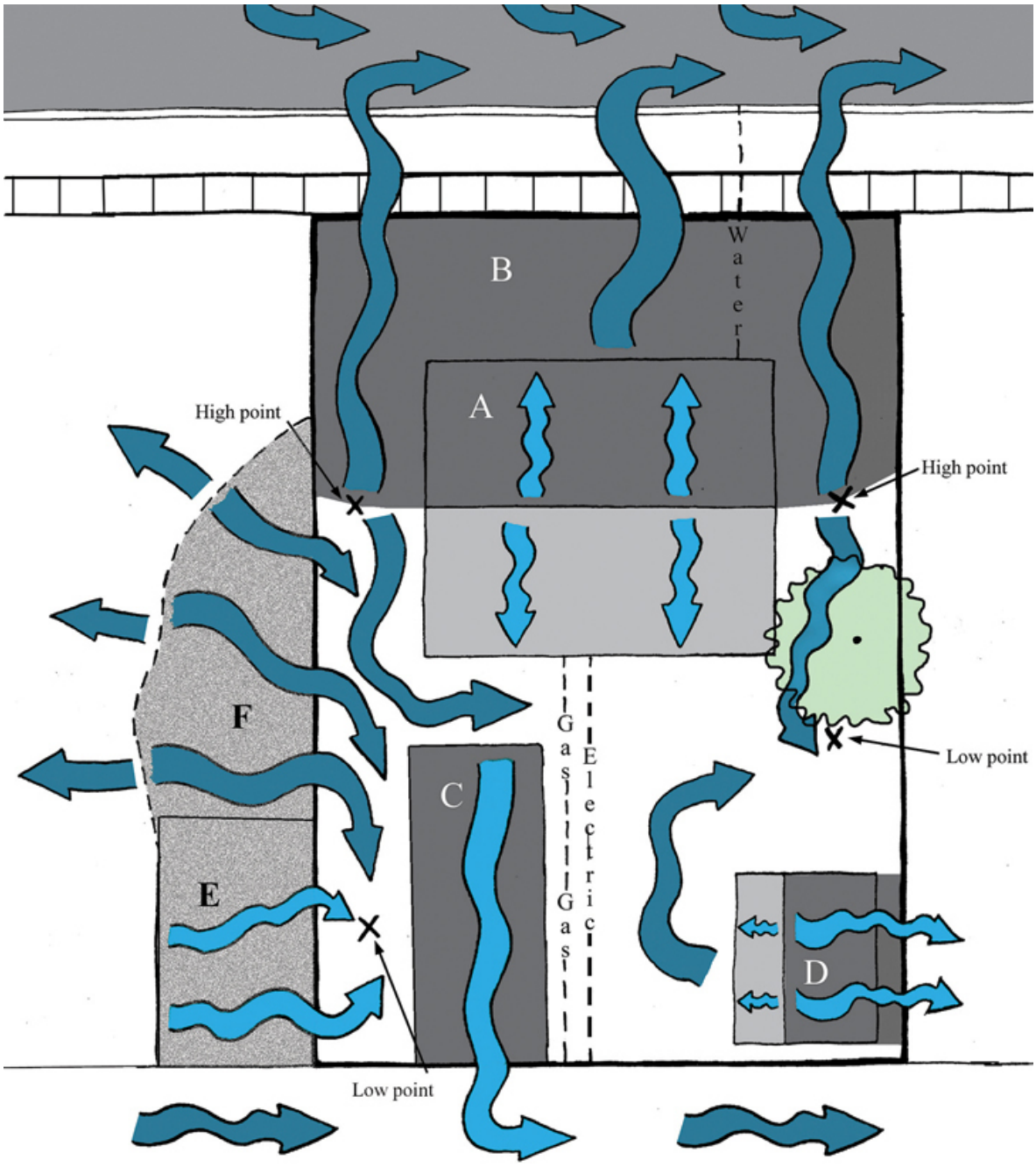


Fig. 1.21. In an average year of 12 inches (305 mm) of rainfall this site receives 32,912 gallons (124,572 liters) of rainfall, gains 2,992 gallons (11,325 liters) of runon from the neighbor's yard and shed roof, and loses about 7,885 gallons (29,845 liters of runoff for a total site rainwater budget of 28,019 gallons (106,052 liters). If the landscape were changed to harvest both runon and runoff, the site's annual rainwater resources could increase up to a total of 35,904 gallons (135,897 liters). Estimated annual runoff and runon volumes off each type of catchment surface are listed with surface material and runoff

coefficient. Still more runoff from sidewalk, street, and alley could be harvested within the public right-of-way to grow public street and alley trees (see chapter 8 for strategies on harvesting street runoff). See box 1.4 for calculations of runoff and runon volumes.

RUNOFF LOST

A. 3,282 gallons (12,424 liters) runoff lost from 462 ft^2 (42.9 m^2) half of metal having a 0.95 runoff coefficient.
B. 2,246 gallons (8,502 liters) of runoff lost from 858 ft^2 (79.7 m^2) section of gı yard having a 0.35 runoff coefficient.
C. 1,818 gallons (6,878 liters) of runoff lost from a 270 ft^2 (25.1 m^2) conc driveway having a 0.90 runoff coefficient.
D. 539 gallons (2,037 liters) runoff lost from 80 ft^2 (7.4 m^2) s ection of shed's asp shingle roof having a 0.90 runoff coefficient.

RUNON GAINED

E. 1,421 gallons (5,379 liters) runon gained from neighbor's 200 ft^2 (18.6 m^2) n shed roof having a runoff coefficient of 0.95.
F. 1,571 gallons (5,943 liters) runon gained from 350 ft^2 (32.5 m^2) sectioı neighbor's compacted dirt yard having a runoff coefficient of 0.60.

Lighter blue arrows denote cleaner, sediment-free runoff.
Darker blue arrows denote dirtier, sediment-rich runoff.

For more thorough descriptions and illustrations of these calculations, see Volume 1, chapter 2. For additional calculations see appendix 2 of this volume.

At a minimum, plan for landscape/exterior water consumption to be less than your average on-site rainfall. Use no more water from municipal sources or private wells than falls on, runs onto, and is harvested and infiltrated at your site. If you have a well, regularly monitor the water level within it. If the water level stays the same or rises things are likely going fine, but if the level is dropping changes need to be made to reduce the groundwater depletion.

To live within a site's rainfall budget, determine your sustainable water income (on-site rainfall and runon), and your water expenses (check your water bill or the meter on your well). Boxes 12.6 and 12.8 in chapter 12 provide water use rates for household water fixtures and appliances. Estimated water needs of plants can be

obtained from the local agricultural extention office (or see appendix 4 in Volume 1). Chapter 11 gives you many tips on estimating plants' water needs through observation, and strategies to minimize their water needs, while boosting plant health and on-site resource production. The goal is to hydrate rather than dehydrate our watersheds, and to infiltrate and enhance more resources than we extract.

Can you do it? Absolutely! It happens naturally all the time. Get out to the wild natural areas and you'll see all kinds of life living in balance without irrigation or human intervention. The wild site's natural water budget will largely determine plant density, with higher density in areas with more rainfall and infiltration, and lower density in areas with less rainfall and more water loss to runoff.

Giving Back More Than You Take: A Goal Leveraging You to Greater Creativity and Dynamism

The idea of having to give back more than you take irritates some people. They see it is as a constraint *limiting* what they can do. I see it as a constraint *enhancing* what we can do. The goal of giving back more than we take pushes us to attain a greater good, which directly benefits us, while also spreading its benefits and resources (not harm) to a maximum of others, both now and in future generations. More lives are then empowered to do the same, cycling still more benefits and resources back to us and others. Thus life steadily *improves* for all, rather than getting worse. This idea inspires us to think more before we act, to be more creative, which in turn enables us to be more productive and efficient for less total resource consumption, cost, and physical effort. Rather than allowing us to take the quick, poorly thought-out route of inefficient short-term ease and waste for instant gratification, it pushes us to take a smarter route of long-term efficiency, gratification, and vibrancy that attains the seventh principle of water harvesting—*maximize beneficial relationships and efficiency by "stacking functions*."

The idea is to get every strategy, and in this case, every earthwork and its vegetation, to perform at least three functions, while sustainably producing more than it consumes. For example, placed and built right, an earthwork alone can passively harvest water, reduce flooding, control erosion, and provide the irrigation water for the vegetation within it. Those plants can be selected to provide food and herbal medicine, provide summer shade for an adjoining building or patio, allow for warming winter-sun exposure, enhance wildlife habitat, and provide fragrant flowers—all the while consuming no more water than is naturally

available on site. The more functions your design freely provides the richer it all becomes, all the while offering a deeper, more-layered beauty.

I can be initially lured to the surface beauty of an ornamental garden, but if the ornamentation is the extent of its use, and it depends on continual inputs/imports of water, fertilizer, and maintenance, I see that its beauty is only skin deep. The attraction quickly fades. However, when I enter into a multifunctional regenerative garden I discover layer after layer of creative integration freely cycling and building multiple resources such as water, fertility, food, habitat, and beauty. This beauty continually grows the more I learn about, and benefit from, the regenerative garden's expanding dynamism.

25. BEGIN WITH CONSERVATION.

Lessen your need for water so your water-harvesting system can provide for more of your needs and you can live within your site's water budget. Such conservation can be achieved by using low-water-use vegetation within or beside earthworks, mulching, recycling greywater within the landscape, using low-flow showerheads and appliances, and practicing integrated design. Always *reduce* before reusing, recycling, or designing anew.

26. HAVE FUN!

Play with these ideas and earthworks as you adapt them to the unique conditions of your site. Each site is distinctive and requires choosing and creatively implementing the techniques that are appropriate for its slope, soils, rainfall characteristics, those living and interacting with it, and the vegetation. Combine existing strategies and invent new ones. Follow the principles, be dynamic, and make a party out of it. Invite friends over to help with your earthwork creation, celebrate its completion, and watch it soak up the rain when it pours from the sky!

CHAPTER 2

Infiltration Basins: the First of Many Rain Garden Strategies

WHAT IS AN INFILTRATION BASIN?

An infiltration basin is a relatively shallow, *level-bottomed* depression dug into the earth (fig. 2.1). This is a primary rainwater-harvesting technique for flat to very gradually sloping land, and is the one people often think of for irrigating trees and other plantings. Among the variations discussed in this chapter are infiltration basins around existing vegetation, and those used to make sunken gardens. Basin planting is particularly appropriate for drylands gardens, reducing water needs by up to 50% compared to raised-bed gardens often found in areas of more plentiful rainfall. Among the Real-Life Examples you'll see how infiltration basins are used as a highly productive and less-invasive alternative to costly retention/detention basins in developments. There's also an intriguing, traditional, very-low-water-use technique of "planting water in pots"—then planting seedlings around the water-filled porous clay pots to tap the gradually seeping water. In the wetter climates of the Northeast, Northwest, and Midwest U.S., landscaped infiltration basins are promoted under the name *rain gardens*.

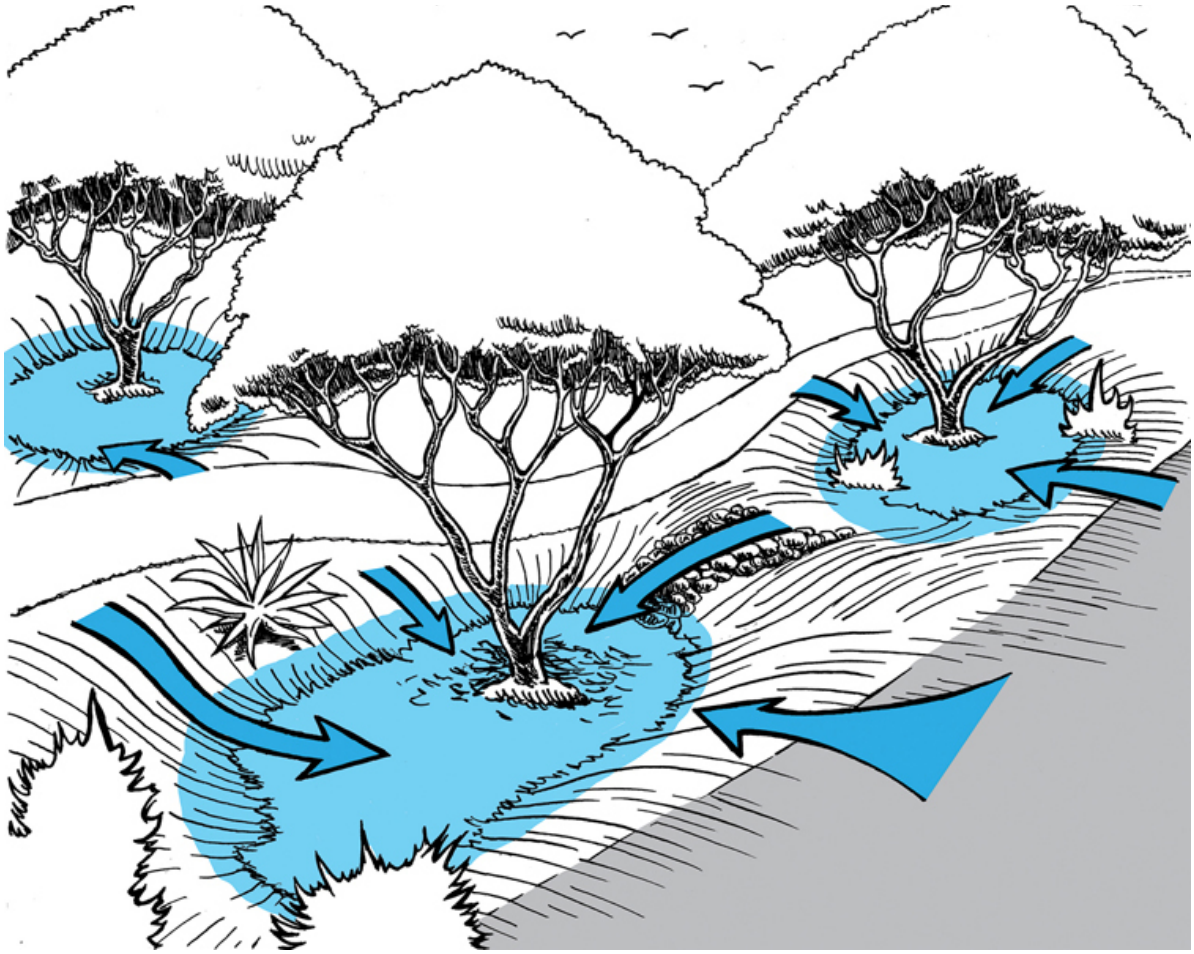


Fig. 2.1. A series of infiltration basins intercepting and infiltrating rainfall and runoff from adjoining curbless street and raised walkway (footpath). Designed correctly, these basins can act as the sole irrigation system for the associated vegetation (once the plants are established), while doubling as a flood control system. 3:1 or more gradual slopes may not need rock stabilization—especially if well vegetated.

The infiltration basin's diameter can extend well beyond the canopy of a mature tree's branches, or it can be one of many smaller basins whose combined surface areas far exceed that of the single large basin. Like a bowl or a catcher's mitt, it collects, infiltrates, and utilizes the rain and leaf-drop that falls within it, while also catching the runoff from the surrounding area, and potentially household greywater too (see chapter 12 for more on greywater). A layer of mulch covers the surface of the basin to soften it, increase infiltration rates, improve soil fertility, and reduce water loss to evaporation. Vegetation is planted within and beside the basin to utilize the harvested water and grow more resources, while further increasing its infiltration.

Dig the basins where you want the water to infiltrate and grow sheltering vegetation close to the water's source, then use the excavated soil to create meandering raised pathways or patios that beneficially drain their runoff into the basins and roots of the associated plants. Any surplus water is directed via spillways from one basin to the next, spreading and infiltrating water throughout the site. On gradually sloping sites the basins can act as a series of stepped basins, much like terraces without retaining walls. The result: transformation of what was once a rather dull and dehydrated flat site to a dynamic one with a wonderful variety of topography—that *harvests* resources rather than draining them.

Compared to other earthworks, infiltration basins have far greater water storage capacity than similarly sized infiltration trenches because they are open, not full of aggregate or mulch. The flat-bottomed infiltration basins are also typically wider than the rounder-bottomed berm 'n basins (b'nbs), whose size and shape are hemmed in by the slope on which they are built. And infiltration basins on flatter sites usually have no berms, so they can draw in the runoff from all directions of the land immediately surrounding them. (Fig. 2.2 shows infiltration basins in a backyard.)

Fig. 2.2. Overhead view of my brother's and my side yard and winter garden. All plantings are located in infiltration basins. All pathways and gathering areas (such as under the ramada) are raised to drain their runoff to the adjoining basins. Rocks stabilize the basins' edge. The 1,300-gallon (4,920-liter) ferrocement cistern in bottom right of picture captures roof runoff for later use in the garden, while its overflow is directed to the citrus tree's basin.

WHERE ARE INFILTRATION BASINS USED?

Infiltration basins work best on relatively flat landscapes or gradual slopes, and do a great job of concentrating water around the plants within the basins (box 2.1). Thus, they are often built as sunken garden beds, water-harvesting tree wells, household greywater drains irrigating an oasis of fruit trees, and interconnected mosaics of vegetated basins throughout a landscape. However, different contexts lead to different approaches.

Box 2.1. What an Infiltration Basin Is Not

An inefficient landscaping practice is planting vegetation on the tops or sides of mounds that are positioned within flat or convex landscapes. Mounds drain rain, irrigation water, soil, and organic matter *away* from the plants and off site, diminishing soil fertility and increasing maintenance needs and water bills.

A slightly less inefficient practice is planting vegetation inside circular berms or earth rings. This practice retains irrigation water and some rainwater and leaf drop, but deflects upslope runoff and leaves dropping beyond the encircling berm, thus reducing the harvested rainwater and organic matter available to plants. See fig. 2.3.

Fig. 2.3. From left to right, a tree planted atop a mound from which water and soil drain away; a tree within a circular berm which diverts area runoff and any leaf drop falling outside the berm away from the tree; and a tree within an infiltration basin toward which the surrounding area is sloped so all direct rainfall, surrounding runoff, and leaf drop is harvested. These trees could've all been the same size at planting, and planted at the same time, though their

current size reflects how the vegetation will respond to the degree to which different landforms drain or harvest resources.

Land disturbance is slow to heal in the dryland environment so it is best to minimize it—especially in areas where there are few resources such as people to do maintenance, runoff water to boost direct rainfall, or supplemental irrigation to get vegetation established and more quickly heal the scar. So, in broadscale dryland restoration projects it is often wise to focus revegetation plantings in natural basins or depressions rather than removing existing vegetation through the creation of new basins. The only dirt moved is that from the digging of a planting hole, and that dirt is cast to the downslope edge of the depression to increase its water-holding capacity. If more invasive basin construction is to happen, try to focus it in areas already disturbed and lacking in vegetation. Along roadways this can work well, since adjoining basins can harvest the road's runoff, delineate what is road and what is not, reduce erosion, and perhaps grow a sheltering shade tree. Dirt excavated to form the basin can further beef up or raise the road base so it stays high, dry, and accessible. And, the easy access to the basins makes it more likely that the structures and plantings will be monitored and maintained when people come through the site.

Around new construction and areas of intense human use—such as homes, schools, and businesses—land disturbance is extreme, but the amount of available resources to mitigate that disturbance is high, thus this is where the creation of infiltration basins makes the most sense, and it is where the basins can best work as multipurpose on-site flood control as well. Basins made in these often compacted and denuded areas can focus roof, patio, and driveway runoff to areas that can infiltrate that water and grow a solar arc (figs. 2.4A, B) of shade trees. This solar arc blocks out the hot summer sun on the east, west, and north sides of the building (in the northern hemisphere), while welcoming in the sun's free source of heat and light in winter, as long as you limit plantings to low vegetation in basins on the south (winter-sun) side of the building that won't shade the windows. (See Volume 1, chapter 4 for more on solar arcs, and see the "Planting Your Rain Garden" section of this chapter for tips on tree species and spacing from buildings.) Greywater from household drains can also be directed to the basins to carry associated plantings through the dry seasons lacking rain, and people can care for new plantings until they are established and able to thrive on harvested rainwater and greywater alone.

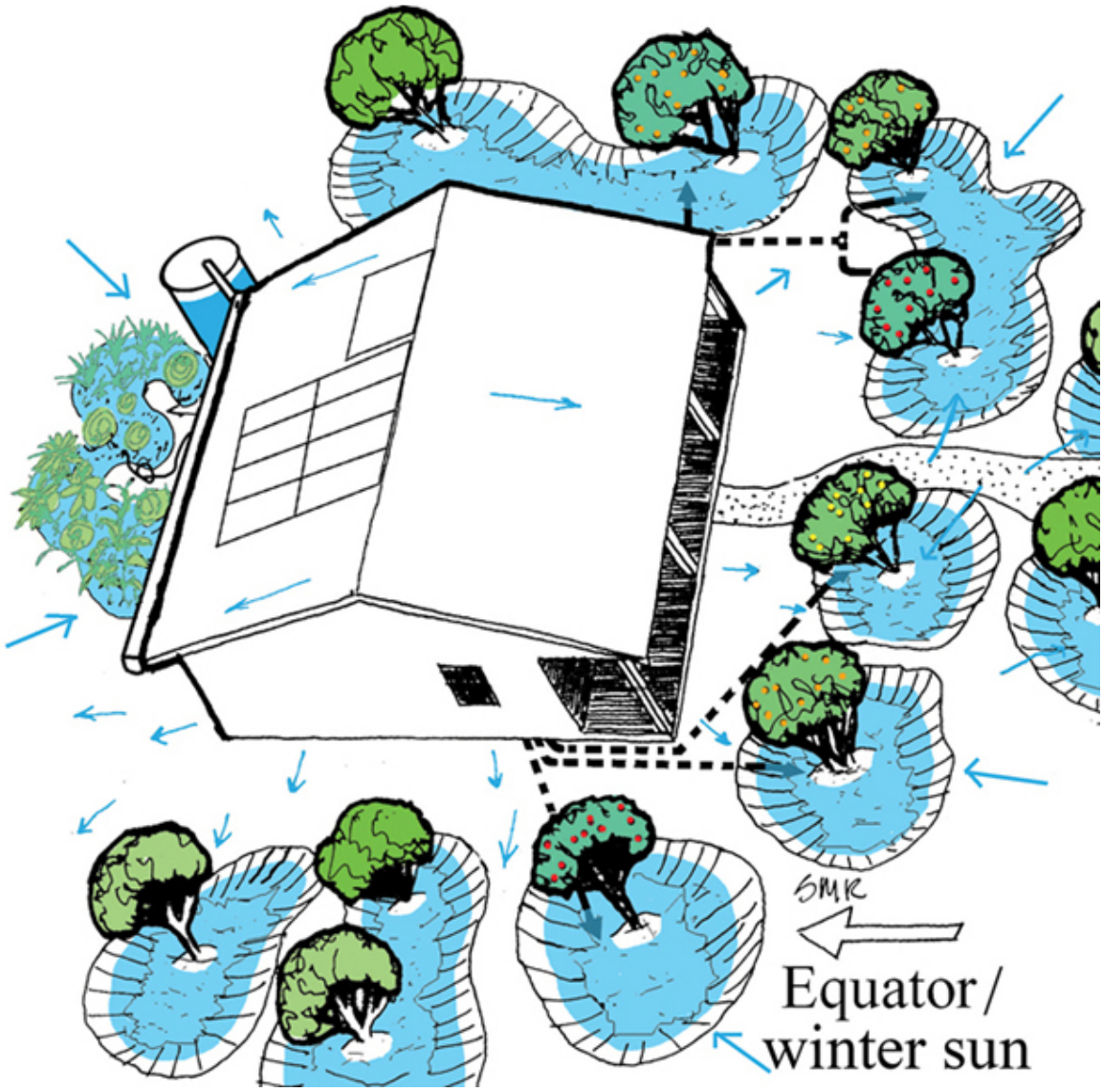


Fig. 2.4A. Water-harvesting infiltration basins placed to help grow a solar arc of trees at 32°N latitude. Basin on the winter-sun/equator-facing side of the house grows a sunken garden. Young trees planted within the basins are irrigated with harvested roof runoff. Greywater (dotted lines) is directed to fruit trees where people gather for convenient irrigation and fruit harvest.

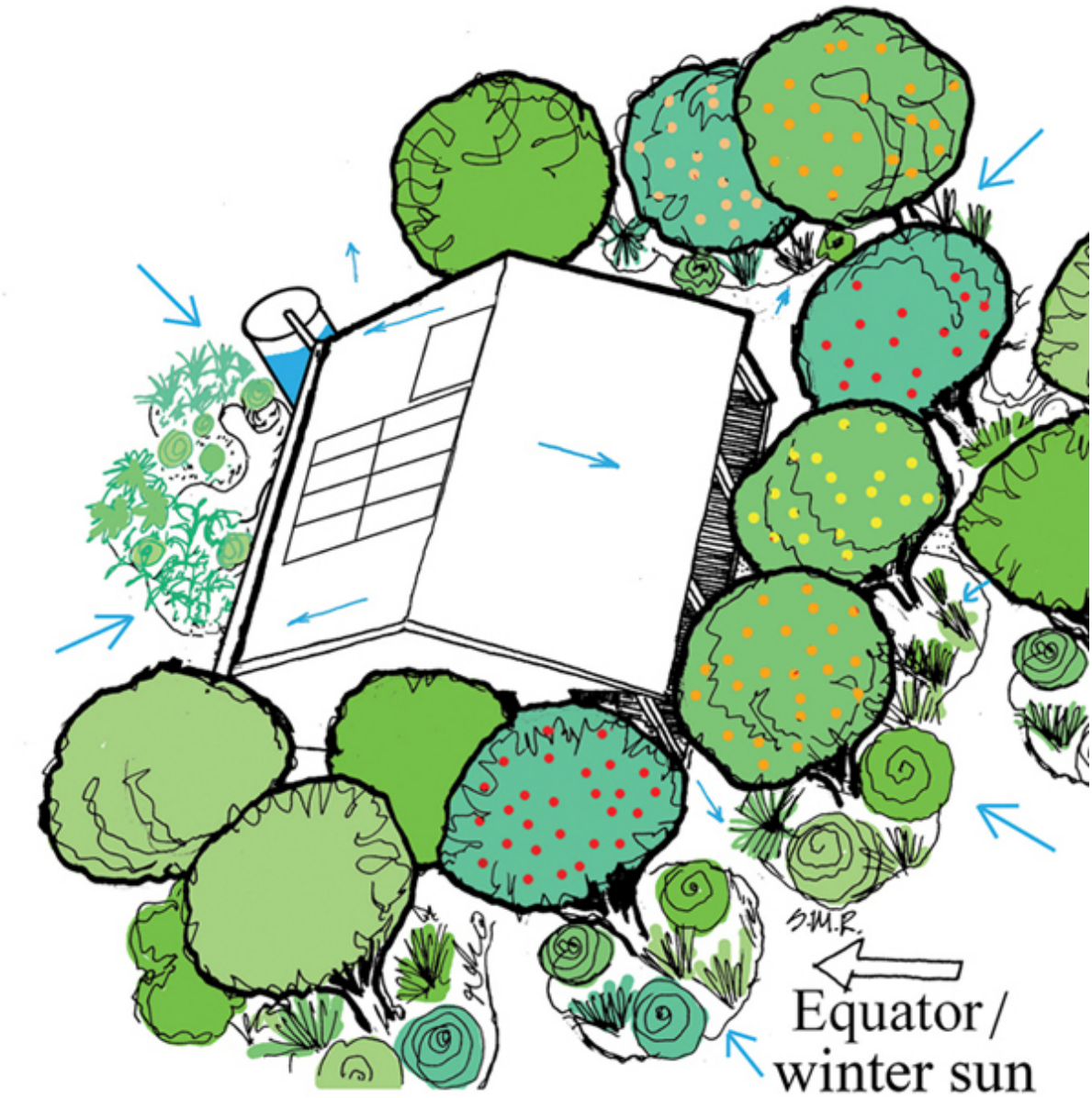


Fig. 2.4B. Trees at full size forming a living solar arc "cool" outdoor summer temperatures by 10 to 20°F (5.5–11°C), while maintaining full winter sun access for free heat, light, and a thriving winter garden. Note how solar panels and solar hot water heater are centered on the winter-sun-facing side of roof by the ridgeline to minimize shading by trees in morning and afternoon.

Infiltration basins should not be constructed within 5 to 10 feet (1.5 to 3 m) of buildings or in drainages. Nor are they appropriate for use in places where groundwater is very close to the surface, which might prevent complete drainage and result in prolonged periods of standing water. Similarly, do not locate infiltration basins over septic drain fields since they could overfill the fields with harvested rainwater.

Mr. Zephaniah Phiri's use of infiltration basins within drainages, which he calls "fruition pits," (see Volume 1, chapter 1, for the story of Mr. Phiri's reclamation of eroded land in Zimbabwe) is an exception to the rule of avoiding drainages. These fruition pits were placed within the confines of large human-made drainage swales having a 1:1,200 slope. Mr. Phiri took extreme care to stabilize the edges of the fruition pits placed within drainages, to make sure they did not get washed out due to unstable soils or heavy runoff.

TOOLS AND MATERIALS

Tools: Infiltration basins have to do with digging, so you'll want a shovel, pick, rake, work gloves, and a wheelbarrow. A Ditch Witch, small skip loader, or backhoe add mechanical muscle when soil is hard or work is more extensive.

Materials: Once your basin is dug, you will need organic matter for mulch, and seeds or plants to bring it to life.

STEPS TO BUILD INFILTRATION BASINS

SITING

Infiltration basins are placed where you want to grow vegetation. They work great near pathways, driveways, alleys, patios, gathering areas, and buildings if they are positioned lower than these hardscapes. That way they harvest rainwater that runs off these paved, compacted, or sealed surfaces. Trees planted in the basins utilize that runoff water and grow to shelter the area.

Mark the outline of your basins with stakes, flagging, surveyor's spray paint, flour (it's nontoxic), or lines scratched deeply into the soil. Borders can be round, oval, curved, or crescent—whatever shape meets your aesthetic needs and works around existing or planned vegetation and structures. I find curves more appealing than straight lines, and I prefer basins of varying sizes and shapes for interest.

If you plan other water-harvesting earthworks, mark these at the same time, so all water-harvesting earthworks are integrated. For example, you could construct a series of earthworks that overflow from one to another. For interconnected basins, position the first basin at the source of runoff (perhaps beneath a roof gutter's downspout or at the top of a slope), and position subsequent basins in a series with the first flowing into the next, and so on. On gradual slopes, terraced basins can step downhill. This distributes rainwater in manageable volumes to

multiple locations throughout the landscape, and keeps erosion in check (fig. 2.5).

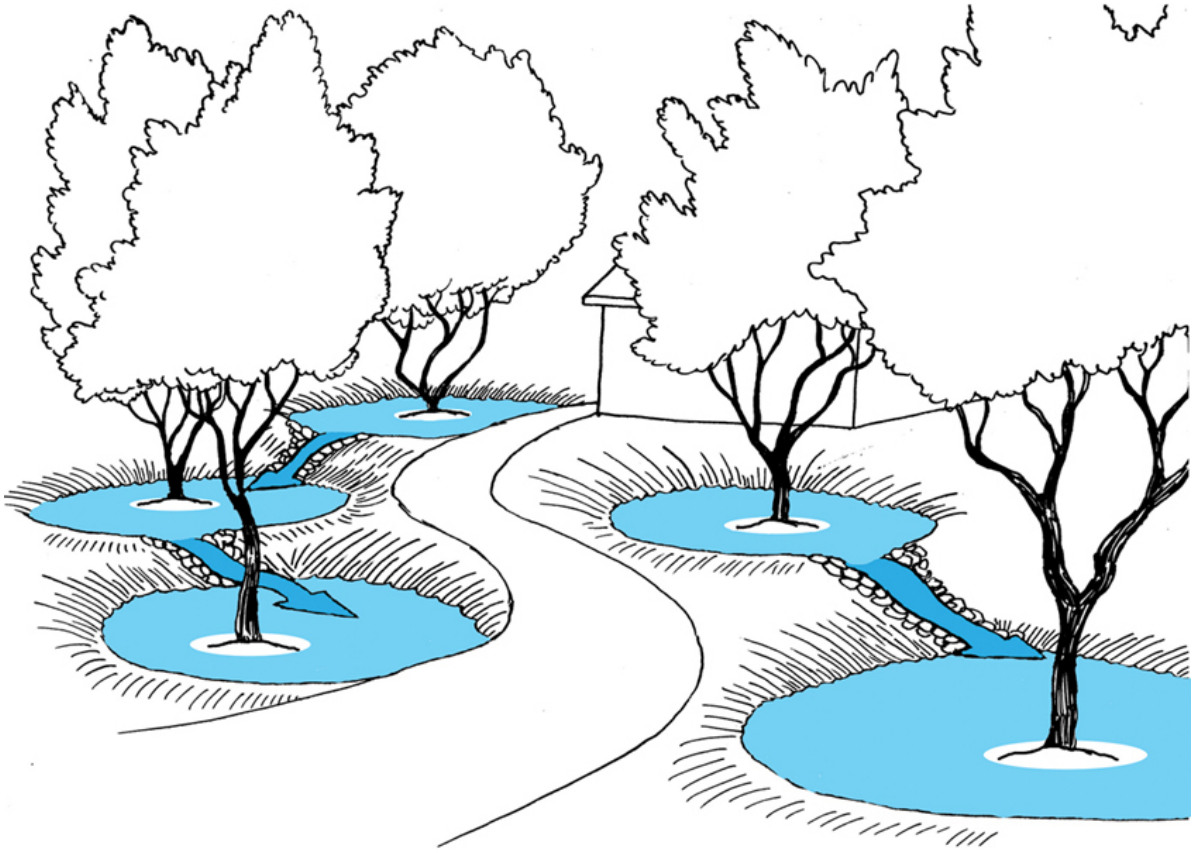


Fig. 2.5. Terraced or stepped basins from which overflow water will flow down a stabilized spillway to the next basin below. The bottom of each basin is lower than the height of its spillway so water infiltrates throughout the landscape—each stepped basin along the way.

If you need paths, raise the pathways and position them between or along the sides of basins so they act as partial borders for your earthworks (fig. 2.6). This can also reduce your digging, because as you cast excavated dirt on the path bordering the basin, this raised basin edge deepens the basin.

Fig. 2.6. A raised path between basins

APPROPRIATE SIZE AND SPACING

Infiltration basins for perennial plantings should be at least 9 inches (23 cm) deep. Don't start any shallower because you'll be adding mulch and over time additional organic matter and silt will accumulate, raising the bottom of the basin. Where I have the space, and the incoming runoff, I may dig basins 18 to 24 inches (45–60 cm) deep. I don't go any deeper because I want to avoid basins that hold more water than will infiltrate into the soil within 12 hours. If berms are created on the downslope side of the basin, they should be at least 2 feet (60 cm) wide to make them durable, and as much as 3 to 5 feet (90–150 cm) wide to double as raised pathways suitable for wheelbarrows, wheelchairs, and easy walking (fig. 2.6). Plan your basins' size to handle the expected amount of direct rainfall and runoff, and size according to the *mature* size of plants you want to grow within the basins. Ideally, the boundary of a basin should extend at least 1.5 times the width of the mature plant's canopy or there should be neighboring basins the plant's roots can reach. This is because most of the plant's roots spread 1.5 to 3 times the width of the canopy, within the top 2 feet (60 cm) of soil, and most of the water used by a plant comes from outside the canopy drip line (figs. 2.7A, B, 2.8).[1]

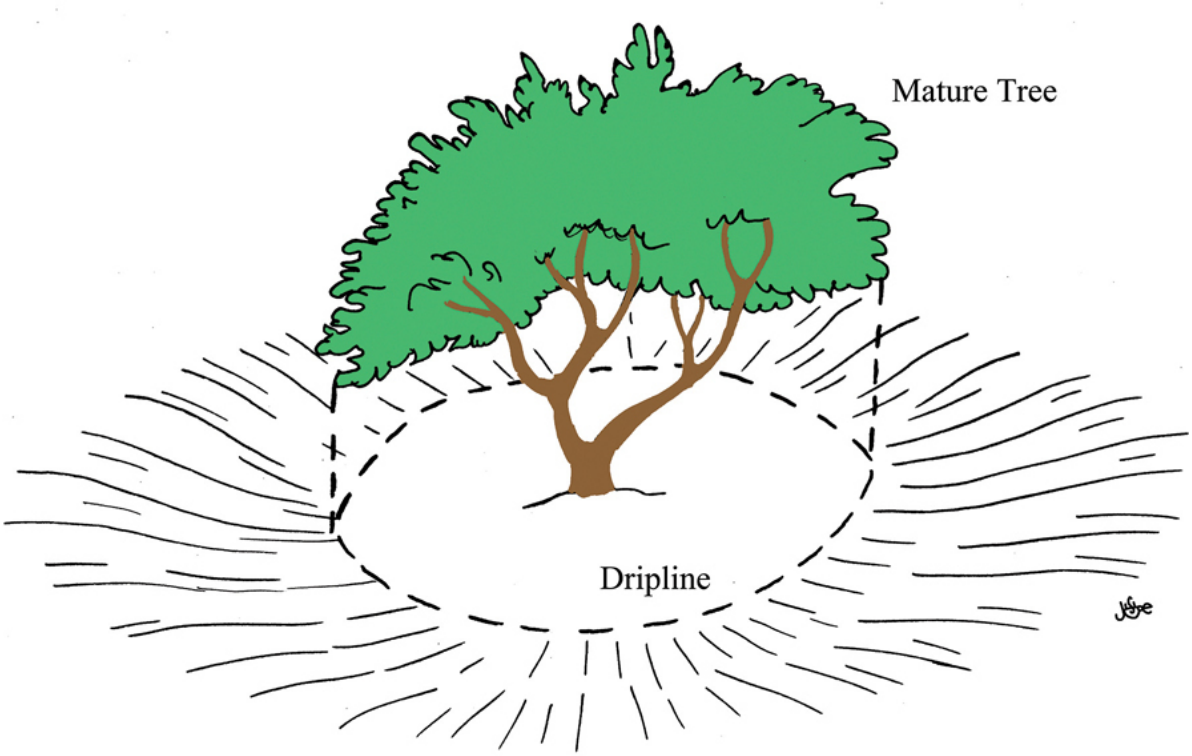


Fig. 2.7A. Ideally, the infiltration basin diameter is at least 1.5 times (and up to 3 times) the diameter of the associated mature plant's canopy drip line, since roots spread, and most water used by many desert plants is drawn from the root zone outside the canopy drip line.[2] However, even one undersized basin or a series of basins is better than no basin.

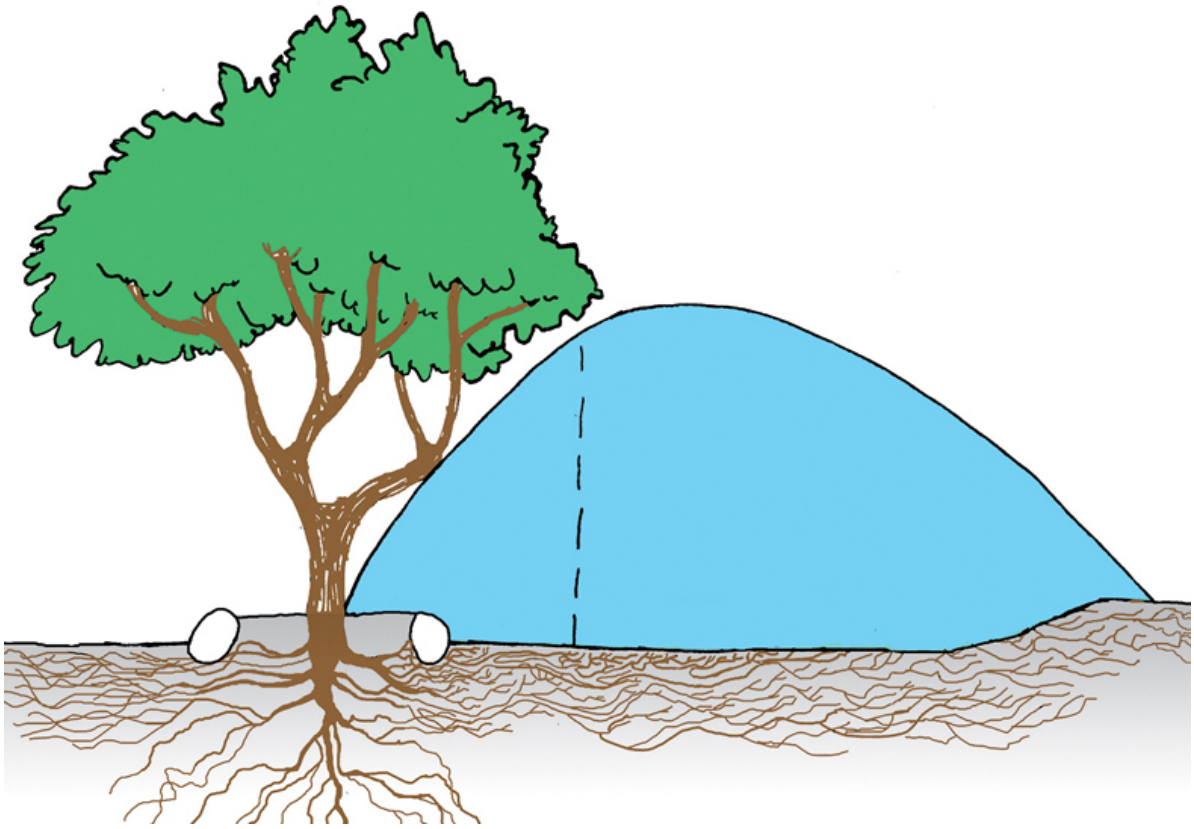


Fig. 2.7B. Think like a tree. The blue shaded area indicates the percent of the water absorbed by the tree roots at a given distance from the tree's center. Adapted from: *Water Requirements of Landscape Trees*[3]

Fig. 2.8. Large basin divided into smaller basins. Roots of trees will extend to surrounding basins.

In addition, most of the plants' leaf-drop is then collected within the depression, and the basin's surface is sheltered by the plants and accumulated organic matter.

In urban areas and smaller yards it may not be possible to create a basin 1.5 to 3 times the width of a mature tree's canopy. The desire for patio space, paths, and other uses must also be incorporated into the layout. In such instances, make the basin as close as you can to the ideal size, and settle for that. A smaller basin is better than no basin. It's also fine to break up a single larger basin into smaller basins with a raised path or section of a raised patio. The roots will find the water accumulating in the low spots (fig. 2.8).

In landscapes with mixed plantings of trees and shrubs, I limit the size of individual basins to no more than 40 feet (12 m) across, yet it's fine to have an area divided into a number of smaller sub-basins that amount to a cumulative basin area much larger than 40 feet across (fig. 2.8). Dividing large basins into sub-basins also helps ensure that harvested rainwater more evenly infiltrates throughout the whole area of each basin. In larger undivided basins water may concentrate in just a few low spots too distant for some of the associated plants to reach with their roots. Box 2.2 enables you to determine basin capacity and volume.

Box 2.2. Calculating Infiltration Basin Capacity or Volume

To calculate the maximum surface water surge an infiltration basin could hold at one time, you need to know the depth of the basin, plus the diameter of a circular basin or the width and length of a rectangular basin (see figs. 2.9A, B). Using this information to calculate basin volume will give you a conservative estimate of the basin's water-surge capacity because it does not take into account any of the water that will rapidly infiltrate into a well-constructed basin's soil and vegetation during the water surge.

These calculations give you approximate volumes that you can use in designing new basins, finding the capacity of existing basins, and/or figuring out how much water will be available to vegetation planted adjacent to the basins. Since these are estimates, the numbers used in the calculations can be rounded to make the math easier. Remember that earthen basins don't typically have straight sides—they typically have rock-stabilized banks with about a 1:1 slope or unrocked slopes with at least a 3:1 slope—and shapes may vary. Just do your best to measure representative basin diameters, lengths, widths, and depths when doing these calculations.

These are the basin measurements you will need:

- **Depth.** Depth is the distance from the bottom of the basin to the top of its rim, or to the top of the lip of the overflow spillway if you have one. See fig. 2.10.
- **Diameter of a circular basin.** Diameter is the distance from one side of a circular basin to the other, measured across the middle of the basin. To get an approximate average diameter, measure this distance about halfway down the depth of the basin (fig. 2.9A). To calculate the radius (R) used in the calculations below, simply divide the measured diameter by 2. If the basin is an oval shape, measure the short diameter and the long

diameter, add them up and divide by 2 to get the average diameter. Then apply the rest o the calculations.

- **Width of a rectangular basin.** Width (W) is the shorter of the two horizontal dimensions of a rectangular basin. To get an approximate average width, measure the width about halfway down the depth of the basin (fig. 2.9B).
- **Length of a rectangular basin.** Length (L) is the longer of the two horizontal dimensions a rectangular basin. To get an approximate average length, measure the length about halfway down the depth of the basin.

When doing these calculations, use the same units for all measurements. For example, all English measurements should be in feet. The resulting basin capacity/volume will then be in cubic feet, which you can convert to gallons using the conversion factor shown in the calculations below.

Metric measurements should be in meters. The resulting basin capacity/volume will then be in cubic meters, which you can convert to liters by dividing cubic meters by 1000.

CIRCULAR BASIN CAPACITY AND VOLUME CALCULATION (FIG. 2.9A):

$$\text{Basin volume} = \pi \times R^2 \times \text{Depth}$$

where R, the average radius, is equal to the diameter divided by 2.
Diameter is measured halfway down the depth of a circular basin.
Fig. 2.9A shows where depth and diameter measurements are taken for this calculation.

Using an example basin (shown in upper left, fig 2.9A) with a depth of 1 foot and an average diameter of 5 feet—therefore a radius of 2.5 feet—the calculation is as follows:

$$\text{Basin volume} = \pi \times (2.5\ \text{ft})^2 \times 1\ \text{ft}$$

$$\text{Basin volume} = 3.14 \times (2.5\ \text{ft} \times 2.5\ \text{ft}) \times 1\ \text{ft}$$

$$\text{Basin volume} = 3.14 \times 6.25\ \text{ft}^2 \times 1\ \text{ft}$$

$$\text{BASIN VOLUME} = 19.6\ \text{ft}^3$$

To convert cubic feet to gallons:

$$\text{Basin volume} = 19.6\ \text{ft}^3 \times 7.48\ \text{gallons per ft}^3$$

BASIN VOLUME = 146.8 gallons, rounded up let's call it 150 gallons

If the circular basin is oval in shape instead of round (fig 2.9A), measure the longer diameter of the basin and the shorter diameter of the basin. Add these diameters together then divide by 2 to get average diameter.
Divide by 2 again to get the average radius.

RECTANGULAR OR SQUARE BASIN CAPACITY AND VOLUME CALCULATION (FIG. 2.9B):

$$\text{Basin volume} = L \times W \times \text{Depth}$$

where L is the average length of the basin and W is the average width, measured halfway down the depth of a rectangular basin. Fig. 2.9B shows where length, width, and depth measurements are taken for this calculation.

Using an example basin (shown in top of fig 2.9B) with an average length of 8 feet, average width of 7 feet and a depth of 2 feet, the calculation is as follows:

Basin volume = 8 ft × 7 ft × 2 ft

BASIN VOLUME = 112 ft^3

To convert cubic feet to gallons:

Basin volume = 112 ft^3 × 7.48 gallons per ft^3

BASIN VOLUME = 837.8 gallons, rounded up let's call it 850 gallons

To estimate basin's annual water-harvesting volume and ballpark dollar per gallon or liter cost

see Equations 8 and 9 in the Calculations appendix.

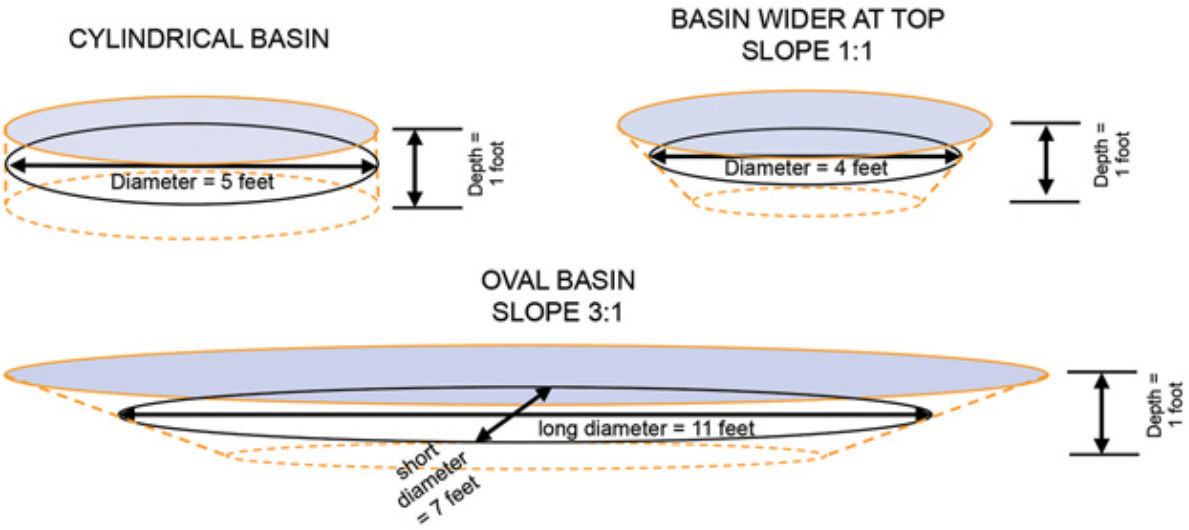


Fig. 2.9A. Circular-basin depth and diameter measurements.

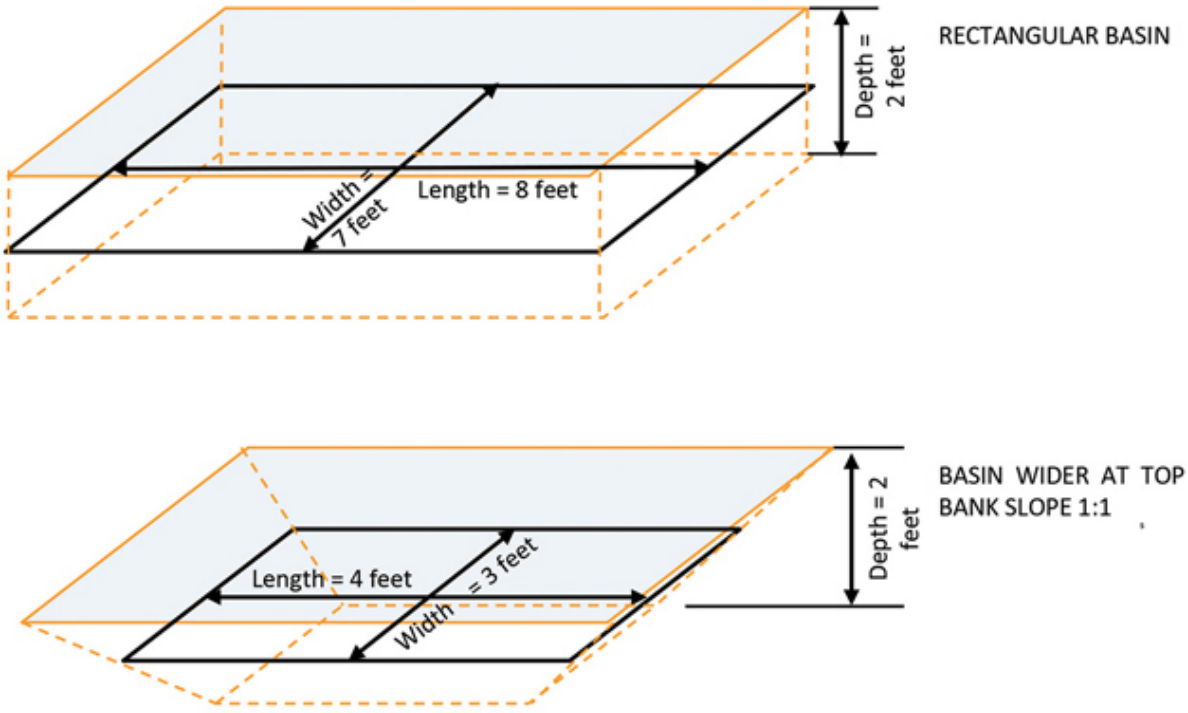


Fig. 2.9B. Rectangular-shaped basin depth, width, and length measurements. Basin at top is used in calculations for rectangular basin in box 2.2.

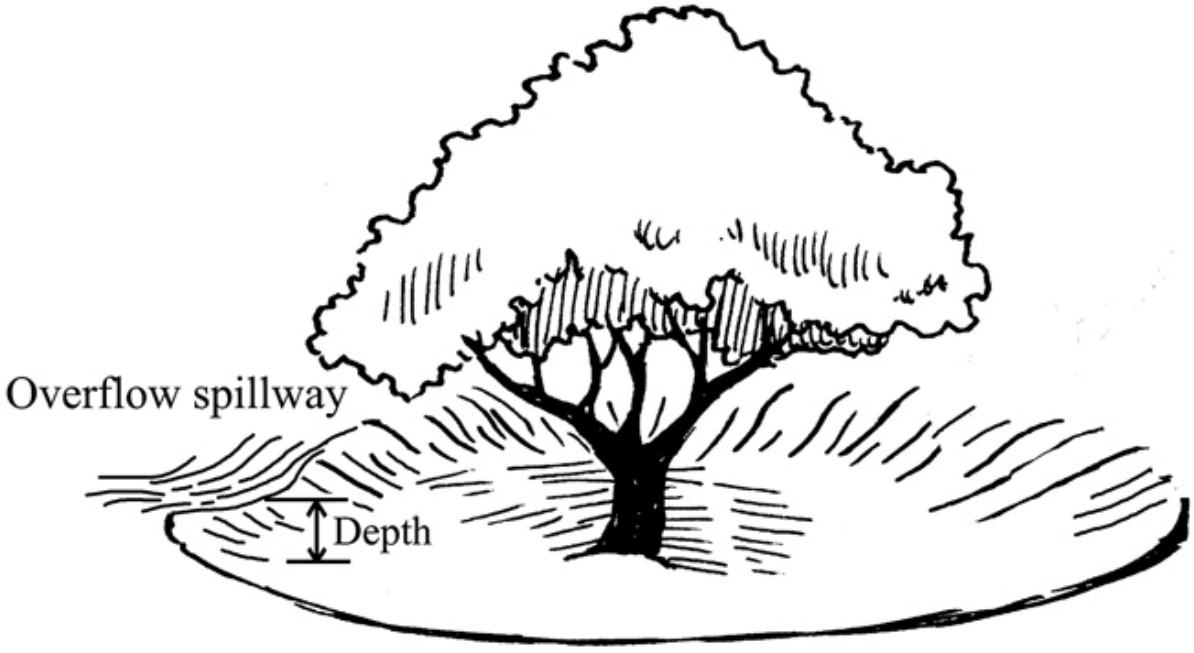


Fig. 2.10. Infiltration basin with spillway, showing depth measurement. See fig. 1.13 for another perspective

CONSTRUCTION

Dig your infiltration basin and grade the surrounding earth so it slopes into the basin and captures runoff water from a large area. The deeper the basin, the more storage capacity and the longer it will last before filling with organic matter and migrating soils. However, I don't recommend more than a 2-foot (60-cm) depth for a basin, since you don't want to hold more water than can infiltrate within 12 hours.

Make the slopes of the infiltration basin's edge gradual and stable for a more welcoming appearance, a safer edge for pedestrians, and less erosion. A 3:1 or more gradual slope (for every 3 units of horizontal length the slope drops 1 unit in vertical height) is typically used around heavy foot traffic areas like sidewalks and patios. However, such slopes of your basin may constrain its depth. For example, if you dig a 6-foot (2m)-diameter basin beside a sidewalk, with a 3:1 slope around the basin's edge, you probably can't go any deeper than 12 inches (30 cm) with the basin because of the limitation of your slope (fig. 2.11).

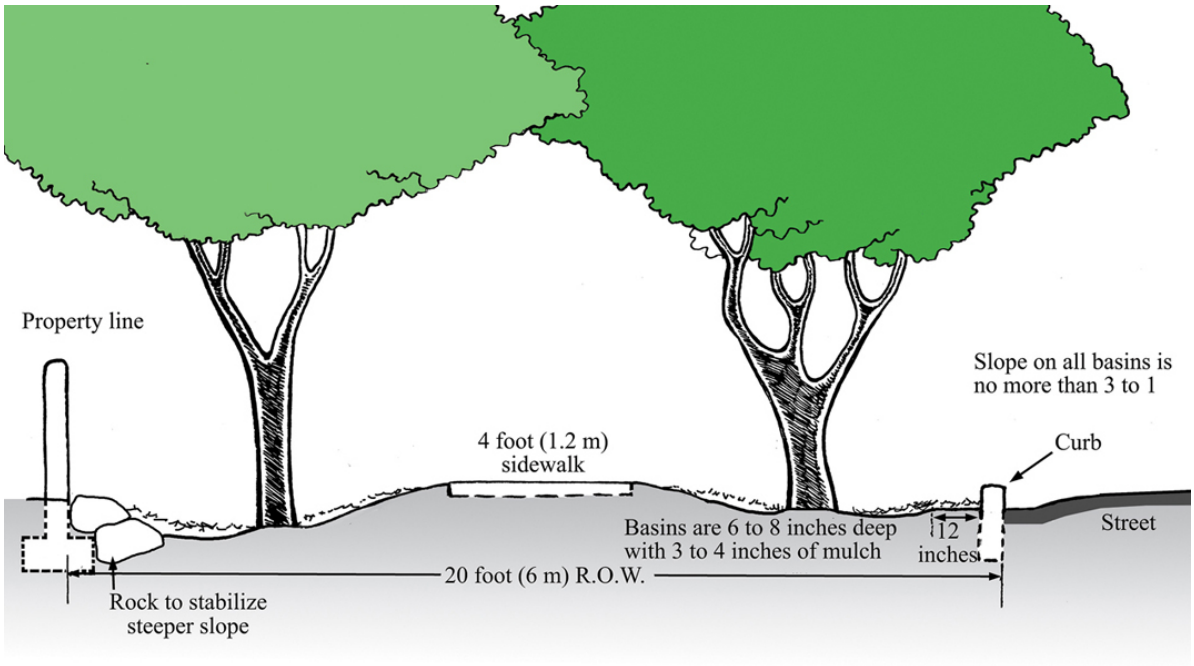

Property line
Slope on all basins is no more than 3 to 1
4 foot (1.2 m) sidewalk
Curb
Basins are 6 to 8 inches deep with 3 to 4 inches of mulch
12 inches
Street
20 foot (6 m) R.O.W.
Rock to stabilize steeper slope

Fig. 2.11. Basin depths constrained by their gradual slopes in a confined space, in this case a 20-foot (6-m) right-of-way with two trees and 4-foot (1.2-m) wide sidewalk. The steepest section of earthen slope between sidewalk and tree is a 3:1 slope. Note the deepest part of the basin is away from the curb to lessen root heave of infrastructure. See figs. 8.44 and 8.45 for how bank stabilization with rock can increase basin capacity in tight spaces.

A steeper slope can be used in areas short on space if stabilized with vegetation or rock (fig. 2.11).

Whenever possible, make the bottom of your infiltration basin *level*. This speeds up and more evenly distributes the infiltration of water throughout the whole basin.

Avoid compacting the bottom of a water-harvesting basin, since that decreases the rate at which water can infiltrate into the soil. Reverse the compaction of the basin that occurs when you excavate it by loosening the soil with a rake. In poorly draining soils, you may need to increase infiltration rates further by graveling, ripping, or aerating the bottom of a basin before planting vegetation and applying mulch.

Use the dirt dug from an infiltration basin to help water flow into, or stay within, the basin. One way to do this is to place the extra dirt on the downslope side of the basin to form a boomerang-shaped berm that increases the basin's storage capacity. Excavated dirt can also create raised paths or patios that drain into the basins. Do not construct a complete ring of dirt around a basin because that would keep additional upslope runoff from flowing into the basin.

Ensure that water drains *away* from nearby buildings (figs 2.12 and 2.13). Placing dirt dug from a basin around the base of a building can sometimes help. However, keep a minimum distance of 4 inches (10 cm) between the level of the dirt and the top of a building's stem wall (typically the level of the floor or the bottom of an exterior stucco plaster). This helps prevent damage to walls caused by direct contact with soil moisture, rainfall splash, or easy entry of subterranean termites.

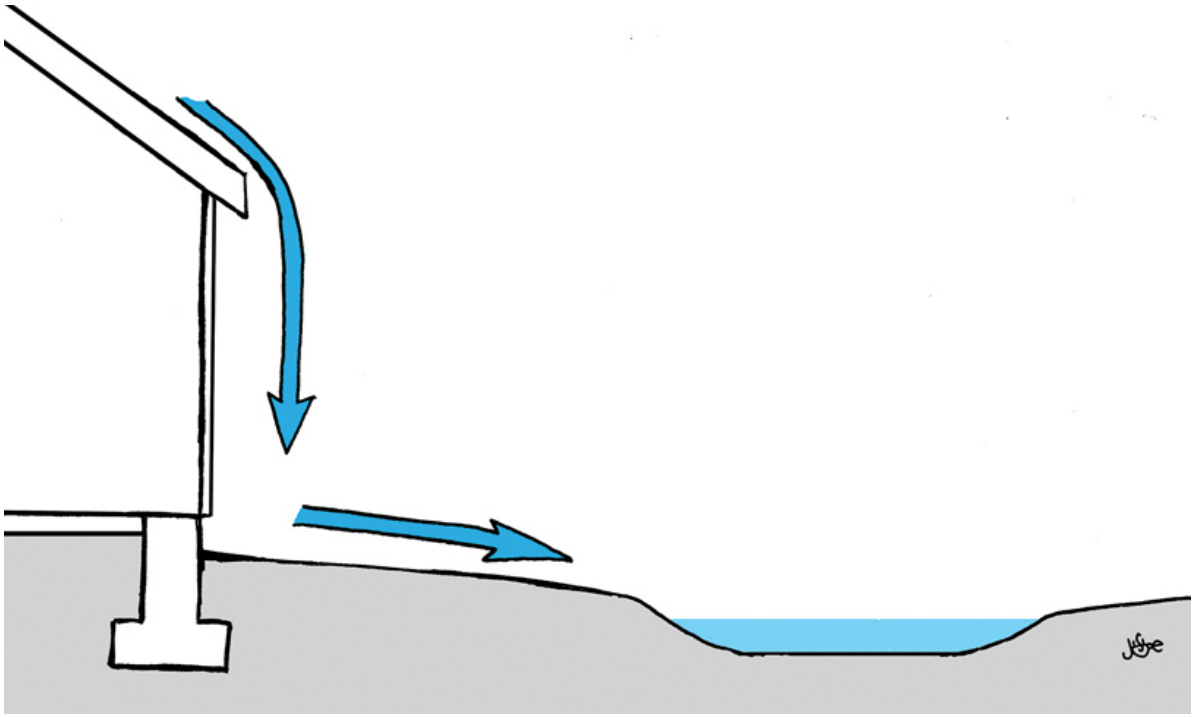


Fig. 2.12. Water from roof should drain away from the building to the basin.

Fig. 2.13. Planted infiltration basins (right side of photo) in small yard. Area between house and basin slopes and drains into the basin. Roots of low-wateruse plants against house are drawn to the basin for water by irrigating them only on the side closest to the basin, then moving drip-irrigation emitter or hose a foot closer to the basin every few months in the growing season, until roots have reached the basin. Roof runoff is also directed to the basins via a downspout, then a pipe beneath the path (dashed blue arrow in back). Greywater from a sink's branched drain (dashed purple arrows in middle) and washing machine's multidrain system (dashed purple pipe in foreground) is also directed to the basin as explained in chapter 12. The basin edge is stabilized and delineated with stone.

Stabilize basin edges to reduce erosion. Stone or brick can be placed around the edge of your basins, if they do not rise above the uphill side of the basin's edge, which would keep precious runoff water out. Smaller perennial plants can also be placed around basin perimeters to beautify and define their edge. (Fig. 2.13 is an example of an infiltration basin in a small yard.)

If you need to haul soil dug from your basins to someplace else, note that excavated soil will expand by about 30% [more if clay, less if sand] due to the now loose, excavated soil having more air within it). Calculate this *swell factor* by multiplying your to-bedug basin volume (see box 2.2) by 30% (or 0.30) then add that to the total volume (of soil to be excavated) in ft^3 or m^3.

LOCATION AND CONSTRUCTION OF OVERFLOW SPILLWAYS

Allow excess water to flow out of a basin to other water-harvesting earthworks by carefully positioning the lowest edge of the basin so it directs overflow water where you want it to go. You can use a diversion swale—a gradually sloping drain described in chapter 9—or a stabilized spillway to lead overflow from one basin to another earthwork (figs. 2.14 to 2.16).

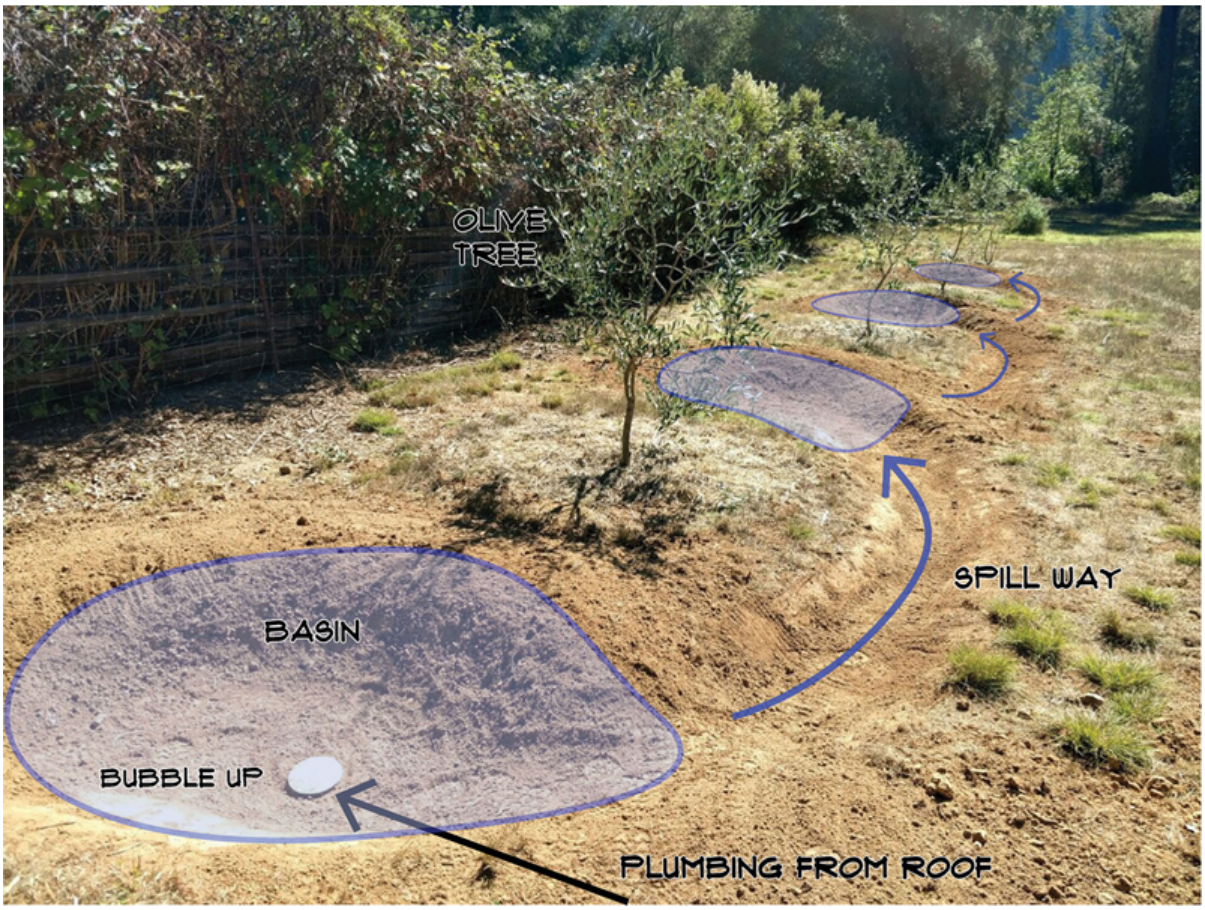


Fig. 2.14. For less water-tolerant trees such as these Mediterranean olives, keep their root crown (base of tree) high and well drained, while basins are within easy reach of the roots. Rock stabilization likely not needed once grass grows back on the gradual slopes. Image by Mauricio Rivera. Design and work by Permaculture Artisans, Sebastopol, California

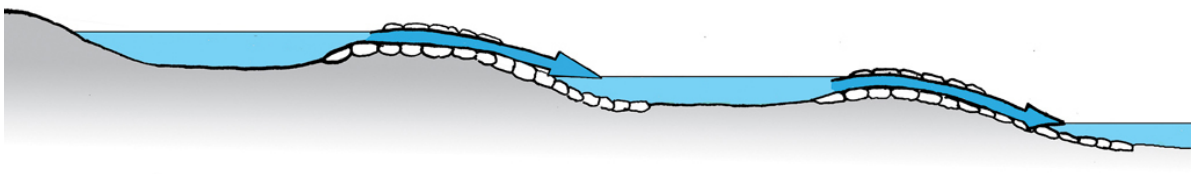


Fig. 2.15A. Stabilized spillways connecting terraced basins on a gentle slope. Note that the bottom of each basin is lower than the top of its spillway so only surplus water overflows the basins, while the majority of the water sticks around and infiltrates. Finished basins are also vegetated and mulched to enhance the infiltration.

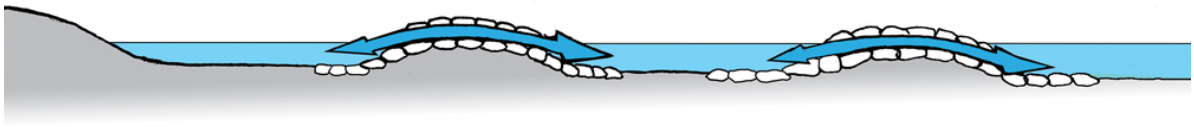


Fig. 2.15B. Stabilized spillways connecting basins on a flat site. Basin depths are the same here, though they can vary randomly. Spillway elevations on such flat sites can all be the same, whatever the basin depth.

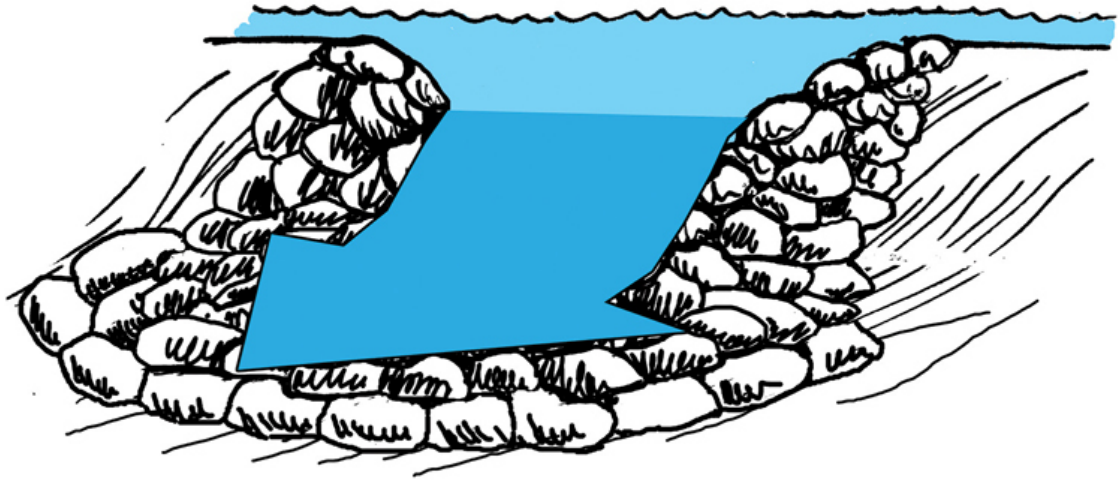


Fig. 2.16. Spillway with stone stabilization. The center must be the low point with raised banks similarly stabilized with stone so the water does not cut a new, more-erosive path. The bottom of the slope where the soil becomes level is also stabilized to calm the faster-moving water that flows down the slope.

The final overflow of your system—at the lowest end of your water-harvesting earthworks and the bottom of your watershed—should always be directed to an existing drainage. Ideally, this would be a natural vegetated arroyo, wash, or creek, though in the urban setting it may simply be a storm drain or the street.

PLANTING YOUR RAIN GARDEN

When planting your infiltration basins, hardy native species are an excellent choice because they are already adapted to the extremes of local climate and geology, and don't need fertilizers or pesticides. Exotics typically need more care, though those appropriate for your area can also work well.

Select and place vegetation according to both a plant's water needs and how much water you expect to harvest within the basin. This approach results in three distinct planting zones or placements (fig. 2.17):

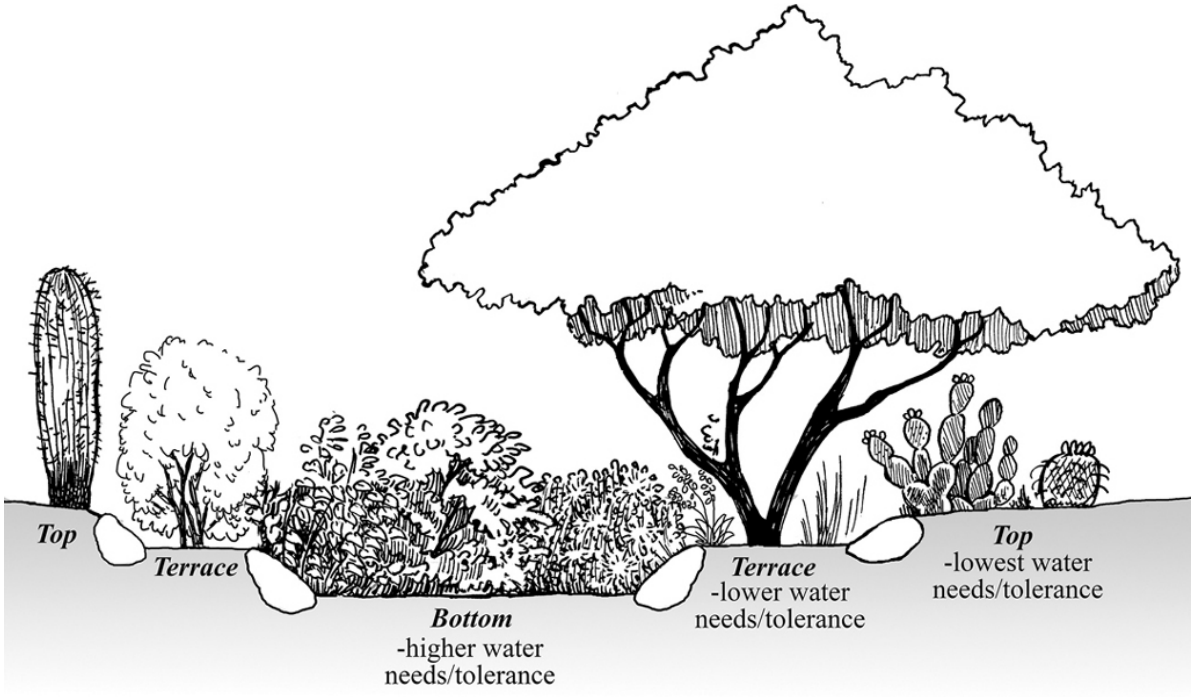


Fig. 2.17. Planting according to water needs and tolerance determines the ideal Rain Garden Zone. See plant lists in appendix 4, Volume 1, latest edition for more. Note: Cold air pools in low spots so cold-intolerant plants may need to be planted on a terrace or outside of basins. See figs. 11.12A-E for additional perspectives.

1. *Bottom Zone*. Place vegetation with higher water needs and a higher water tolera in the bottom of your basin. Such plants naturally grow in drain-ages or floodplains and are accustomed to periodic inundation by water and sediment. Velvet mesquite, canyon hackberry, blue palo verde, and desert willow are indigenous examples in southern Arizona. Date palms are an exotic example.

2. *Terrace Zone*. Plants with lower water needs, a lower tolerance for inundation, c preference for good drainage are suitable for the sloping sides or terraces of the basin. These are naturally found growing in areas unlikely to be periodically inundated with water or sediment. The poorer your soil drainage (heavy clay so drain poorly), the higher you should plant this vegetation in relation to the bot of the basin.

These plants can also be planted in *gradually* sloping dirt pedestals raised 4 to 10 inches (10–25 cm) above the bottom of the basin. This helps prevent disease by keeping water, soil, and mulch from standing against the base of the vegetation. The elevations of these pedestals should *not* exceed the elevation of the basin's edge or you'll begin to get more of a water-draining system than a water-harvesting system. No pedestal should have a steep or even moderate slope or it will quickly erode away. Foothills palo verde, stone-fruit trees, and citrus trees are climate-appropriate examples for my area.

3. *Top zone*. Vegetation that is drought-hardy or water-and rot-sensitive is planted the periphery of basins. The base of the plant remains high and dry, while the r can grow underneath and around the bottom of the basin to access the water as needed. Avocados, carob trees, and native cacti are examples.

If planting by seed, scatter a diverse seed mix of native annual and perennial wildflowers, grasses, shrubs, and trees with desirable growing characteristics throughout the basin, and rake it into the top 1/4 inch (0.6 cm) of soil. Various plants will germinate and survive within their preferred microclimates in the basin. Moisture-loving species succeed more readily in bottoms, while drought-tolerant plants succeed on drier slopes. If you are seeding, avoid mulch or limit it to a very sparse application and depth of 1 inch (2.5 cm) or less. A thick layer of mulch inhibits germination of both weed seed and the seed you want to germinate. Once your plants are at least 6 inches (15 cm) tall you can thicken the mulch.

For further information on appropriate plantings and how to plant, see chapter 11 on vegetation.

While it's important to construct the outer boundary of the basin to accommodate the adult plants or tree, it's equally important to make an additional shallow internal depression in a 2-foot radius (0.6-m) around new plantings to ensure that in small rainfall events, or during irrigation, the water is concentrated around the small plant during the critical period of initial establishment. Deep-pipe irrigation or rock tube irrigation (see chapter 5, Variations section) can also work well for plant establishment in place of such a shallow depression.

Notes on planting a solar arc of basins around a building

Trees with a mature canopy 25 feet (7.5 m) in diameter should be planted 10 to 15 feet (3–4.5 m) from the east and west sides of buildings to provide maximum passive cooling in hot months[4] (see figs. 2.4A, B). The taller the tree will grow, the farther from the house it can be—and should be—if you don't want to excessively shade solar panels and solar water heaters on the roof.

Spacing of the vegetation from a building will vary from site to site. The higher the fire threat or the taller the vegetation, the farther the plants will be placed from a building. The lower the on-site water resources, the more sparse the planting density will be, and the plants will be selected for lower water use.

To avoid damage to the house, do not use trees with shallow or invasive root systems or those susceptible to storm damage, such as eucalyptus, Chilean mesquites (*Prosopis chilensis*), African sumac (*Rhus lancea*), cottonwoods (*Populus fremontii*), or pepper trees (*Schinus* spp.).

MULCHING

After planting, lay a 2- to 4-inch (5–10 cm) layer of organic matter mulch over the entire surface of your basin, except right around the base of your plants where only a very thin layer of mulch should be applied. Wet mulch against the base of a plant may encourage crown rot, but within the basin it increases water infiltration, reduces water loss to evaporation, and makes a basin appear shallower while delineating its edge. A thinner layer of mulch works better where the basin only receives direct rainfall, as in a light rain you don't want the mulch to keep water from reaching the soil. A thicker layer of mulch works well where the basin harvests greywater or additional runoff such as from a roof's downspout or a patio, where enhanced infiltration is a greater need. (See chapter 7 on mulch.)

MAINTENANCE

Check your infiltration basins periodically, especially during or just after heavy rain. You may need to stabilize basin edges, especially along curving paths where folks like to cut corners. Boulders, rock, and bulky vegetation stabilize soil and deflect shortcutters.

If basins are quickly filling with sediments carried by runoff from upslope areas, construct additional water-harvesting earthworks to capture and filter that runoff before it gets to your basins. If you can't access the upper watershed because it's a neighbor's property or for some other reason, plant vegetation on contour or

consider a sheet flow spreader (chapter 10) just above your basins to sift and slow the incoming sediment-rich runoff.

If a downspout erosively pours water over the slope of a basin's edge (fig. 2.18A), stabilize the spillway with either rock (fig. 2.18B) or black plastic corrugated drain pipe that daylights a few inches above the mulch covering the bottom of the basin (fig. 2.18C).

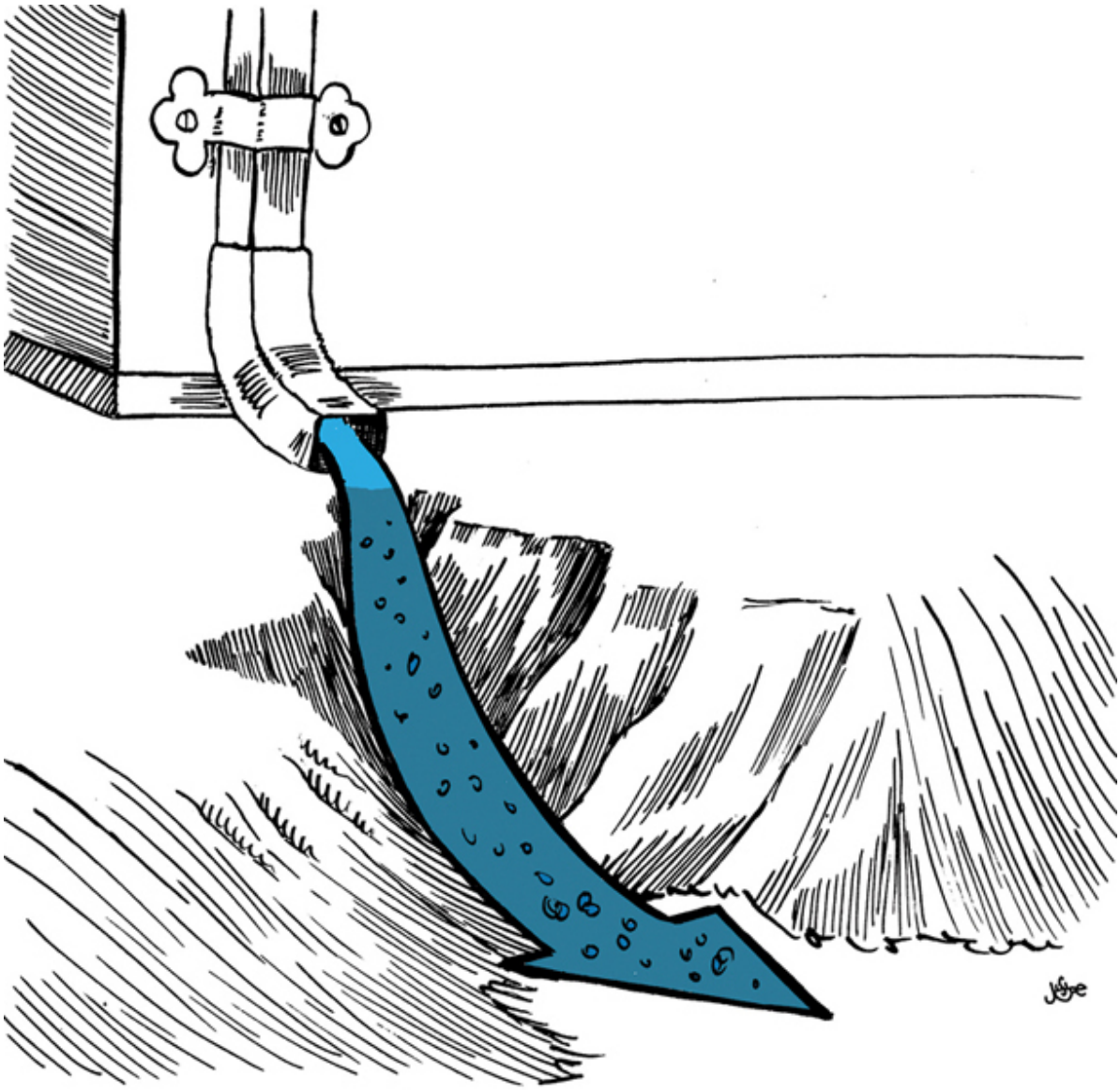


Fig. 2.18A. Runoff erosively flowing over a steep slope

Fig. 2.18B. Stone-stabilized downspout spillway, otherwise known as a *rock-mulch rundown* See chapter 10 for more details.

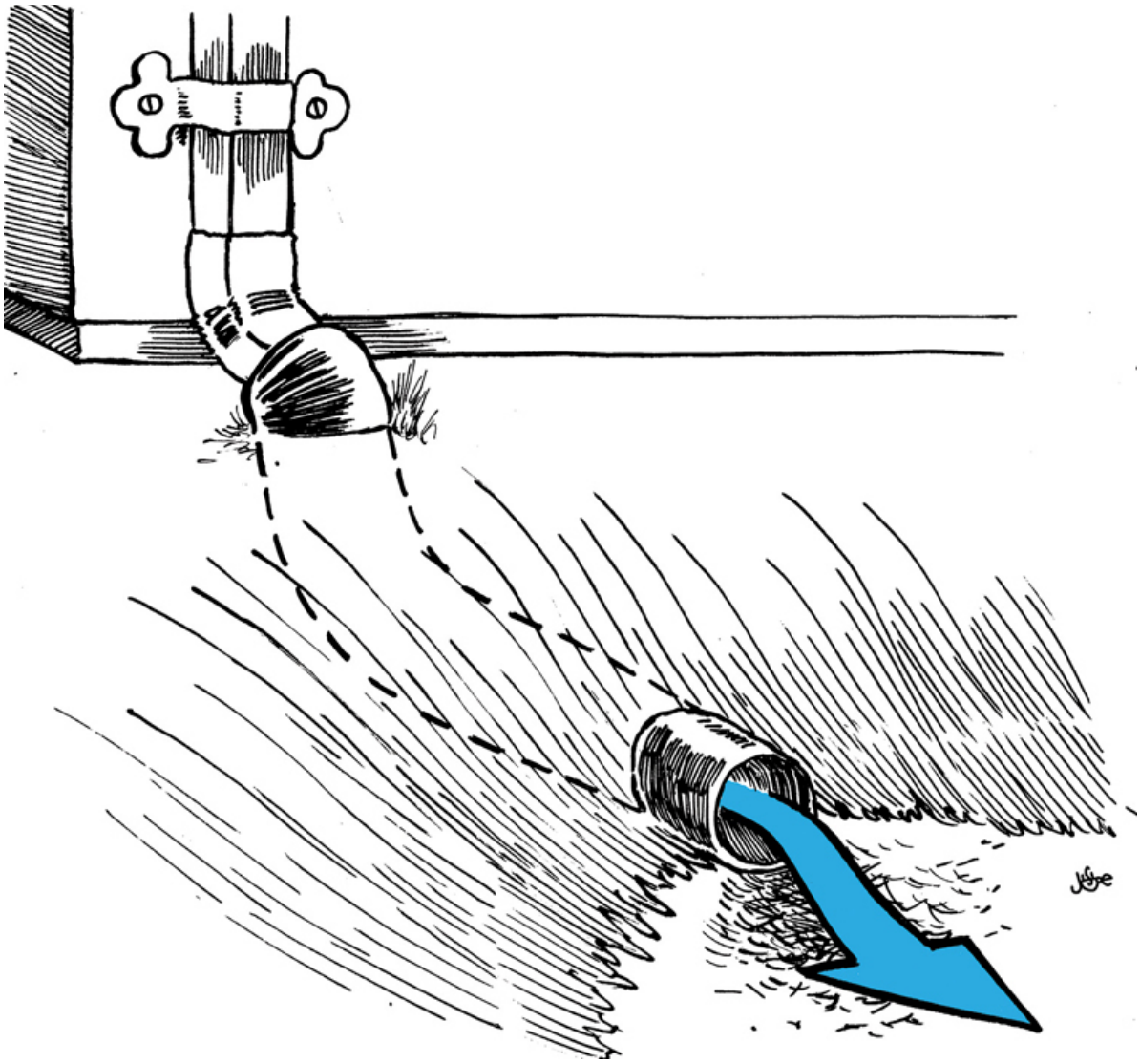


Fig. 2.18C. Calmly outletting downspout flow above the mulch within a level basin so debris does not back up in the pipe. Ensure the pipe slopes into basin so no water sits in the pipe where mosquitoes could breed. Bottom of pipe must be a minimum 3 inches (75 mm) above top of mulch in basin to avoid clogging.

Reapply mulch as it decomposes. This is easily done for free just by letting leaf and fruit drop accumulate in the basin, along with prunings cut up with hand pruners to 4-inch (10-cm) or shorter lengths.

VARIATIONS OF INFILTRATION BASINS

BASINS AROUND EXISTING VEGETATION

You can dig infiltration basins beside existing young trees and shrubs (fig. 2.19) —beyond the drip edge of their canopy—where their roots will grow to access the harvested water. I emphasize young plants, because there is no need to dig basins around a healthy mature tree or shrub that is doing fine without them. In addition, some sensitive trees, can be easily damaged or killed by disturbing their surface roots.

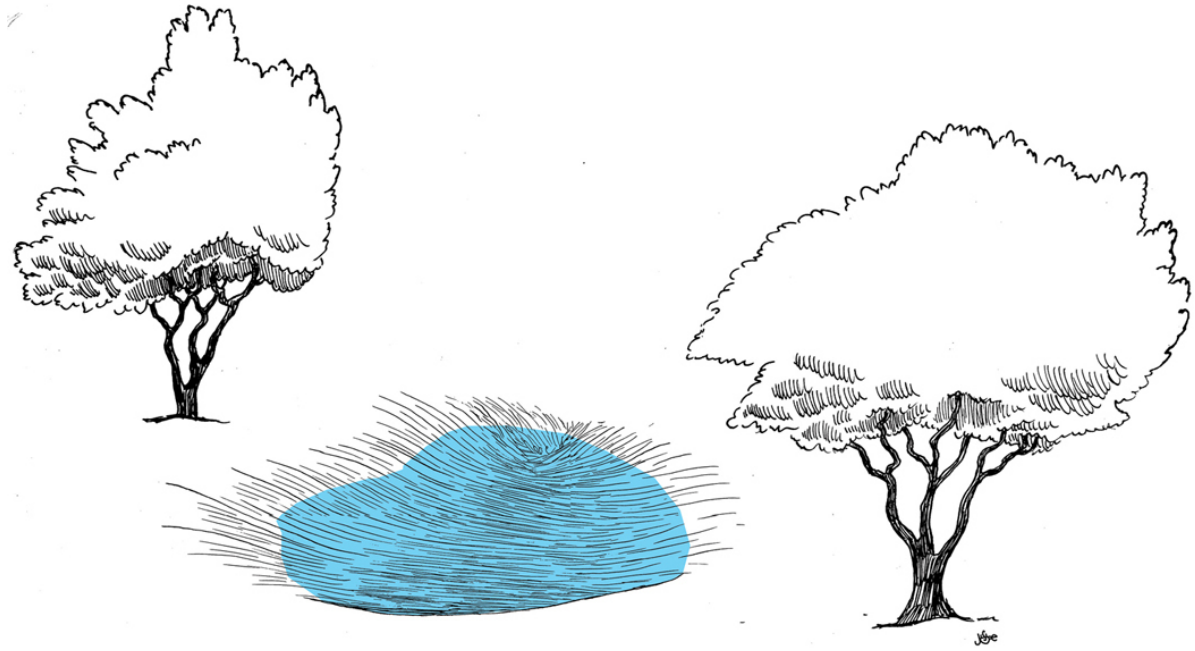


Fig. 2.19. A basin made between two young trees, and ready for a surface mulch to be applied

On sloping land, rather than a basin construct a boomerang berm (see chapter 3 on berm 'n basins) on top of the soil on the downslope side of the plant, since this will disturb fewer roots.

BERMS FORMING BASINS AROUND EXISTING VEGETATION

On densely planted flat ground, you likely will not want to dig basins that could disturb existing plant roots, but you may want to bring in dirt to make a perimeter berm that holds all on-site rainwater and perhaps runoff from a nearby roof. Just make sure your earthworks won't direct water to flood anything you don't want flooded such as a house. Use a water level to make sure the top of your berm is lower than the threshold of your doorway or any vent openings beneath the floor (figs. 2.20A, B).

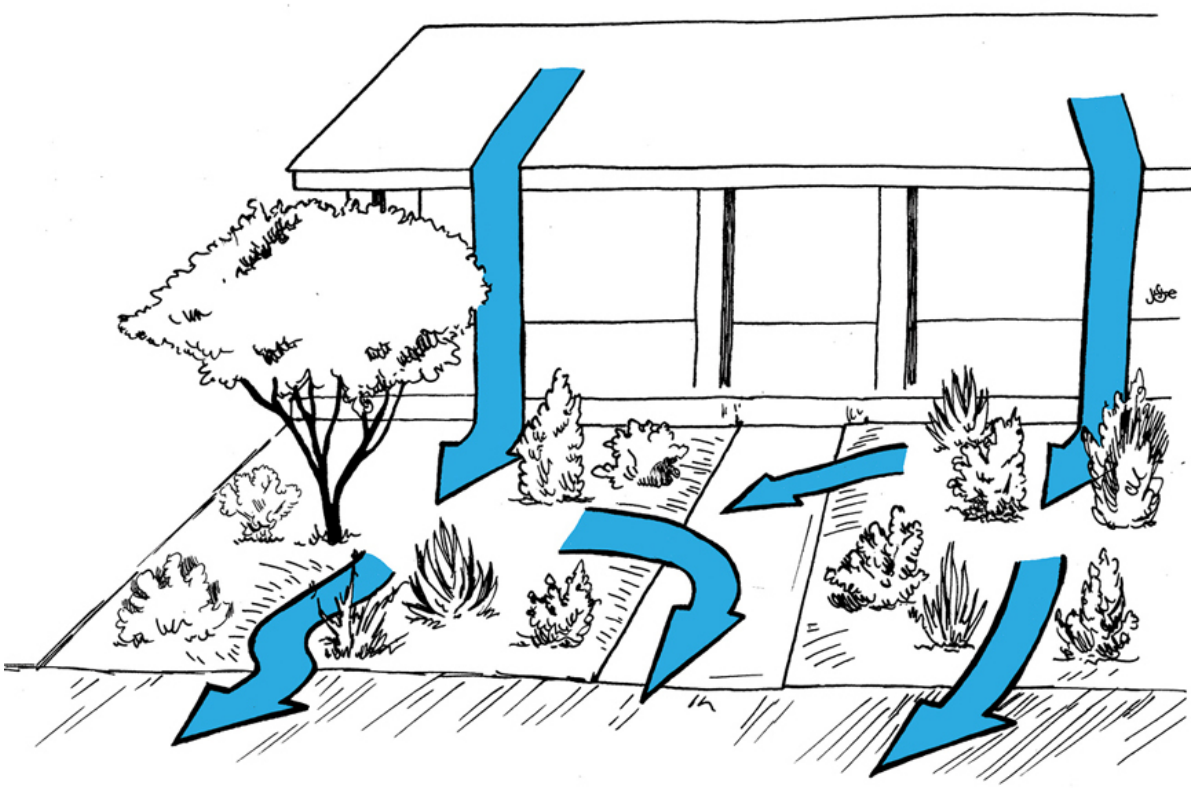


Fig. 2.20A. A yard with existing vegetation that loses runoff in big storm events

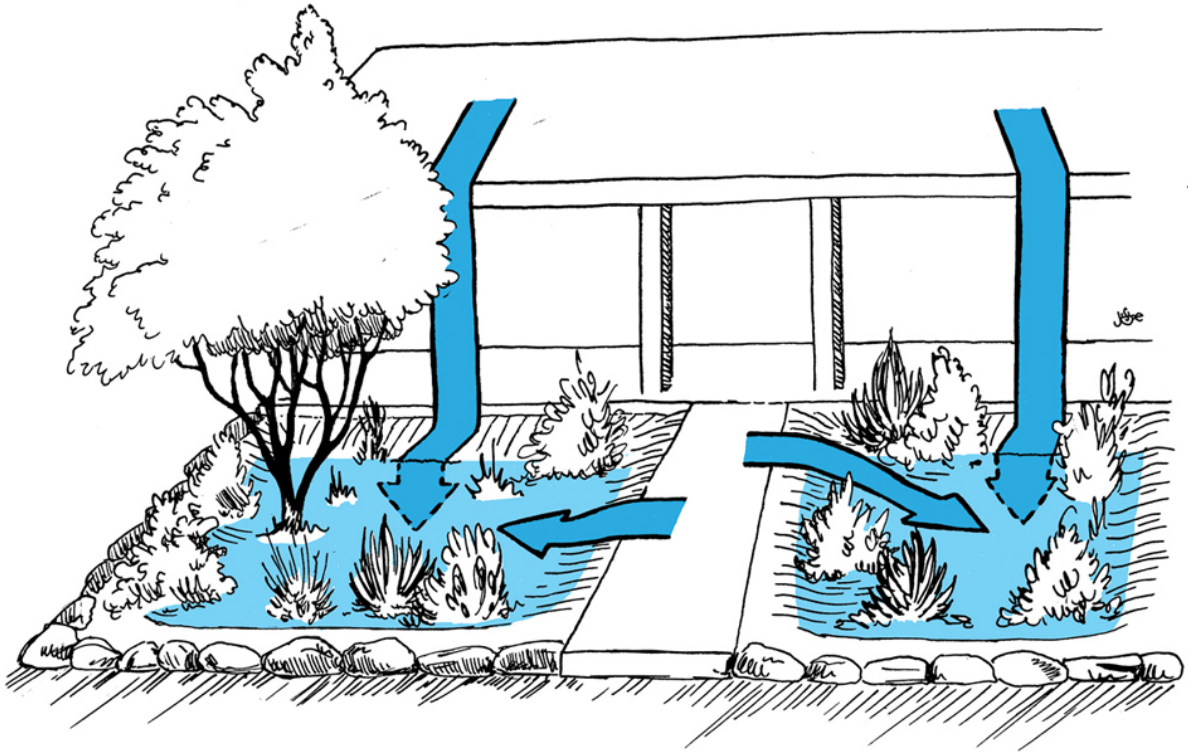


Fig. 2.20B. The same yard after dirt was brought in to create a perimeter berm. Now runoff sticks around and infiltrates the soil. The berm must not be made so high that harvested water could flood the house or anything else you don't want flooded. Existing pathways within the berm may need to be raised to keep them high and dry, and may then double as part of the berm. Note how the now-raised walkway creates a berm dividing the yard into two subbasins.

SUNKEN GARDEN BEDS

I've found sunken vegetable garden beds 25 to 50% more water-efficient than raised beds. Sunken beds hold both the rain that falls into the planting area and the runoff that drains into them from surrounding areas. Raised beds often do the opposite.

As the guide *Food from Dryland Gardens* points out, the raised earth around sunken basins provides protection from the drying winds and sun for the moist soil, young seedlings, and transplants (fig. 2.21). Conversely, in hot dry conditions, raised beds expose a lot of surface area to the sun, which increases soil temperatures, accelerates evaporation, and leads to salt buildup in the growing area.[5]

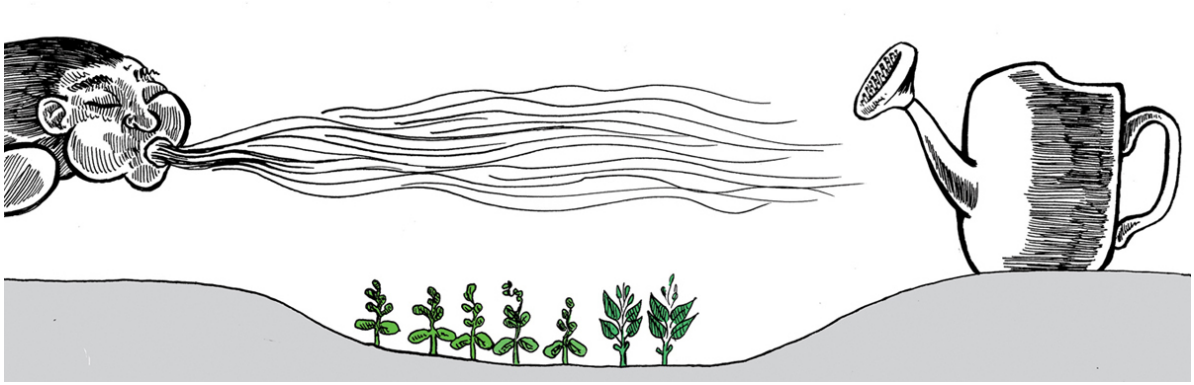


Fig. 2.21. The beneficial microclimate of a sunken garden basin

Dig sunken beds no wider than 4 feet (1.2 m) so you can reach all plantings without stepping into and compacting the bed. Dig down about 18 inches (46 cm) to break up the soil, and amend the loosened native soil with aged compost or manure at a ratio of 1 part soil to 1 part aged or composted manure (I amend the soil as such only for the planting of annuals; perennial plantings get amendments only in the form of an organic surface mulch). Excess soil can be used to make a raised path around the bed (fig. 2.22).

Fig. 2.22. Sunken garden beds

SEASONALLY ROTATING AMONG SUNKEN, GROUND LEVEL, AND RAISED SUNKEN GARDEN BEDS

In some climates, it's wise to rotate the growing of your vegetables between garden beds of varying topography based on seasonal rainfall and temperature swings. In the temperate coastal areas of the western U.S., with heavy winter rains and little summer rain, sunken beds can work great for annual summer crops. Level mulched garden beds positioned at the same elevation as the surrounding landscape are better for annual winter rainy season crops since they help avoid oversaturation—especially with clayey soils. Raised or ground-level perimeter pathways of mulch further help sponge up excessive moisture in wet times and reduce its loss from the garden beds' soil in dry times.

In cold climates, a raised form of the garden bed enables dark soils to more quickly warm up for quicker germination of seed and faster plant growth in the spring. Raised beds are made of a raised section of earth on which annual garden plants are planted. A sunken garden bed can be made atop this by making a perimeter berm of earth to hold, and maximize the potential of, direct rainfall or irrigation water. In the wet season, the perimeter berm of the raised bed can be removed for better drainage if needed.

Play with these strategies and see what works best for you. Experiment with modifications and share your results.

MULTIPLE FUNCTIONS OF INFILTRATION BASINS

INFILTRATION BASINS GROWING A "LIVING FENCE"

Infiltration basins can be located along or near property lines and planted with appropriate vegetation to create living screens of plants. Refer to fig. 2.13 for an example of an integrated use of infiltration basins in a small urban yard.

INFILTRATION BASINS AS ALTERNATIVES TO FLOOD-CONTROL DETENTION AND RETENTION BASINS

New developments are required to create on-site structures to mitigate their potential contribution to downstream flooding and water contamination. This is typically done by constructing large detention/retention basins at the lowest elevations of the site to hold on-site runoff and associated contaminants by "detaining" a portion of the water before allowing it to slowly flow offsite, and permanently "retaining" another portion of the water on site by infiltrating it into the ground. This works to a degree, but leaves the majority of the site drained and dry.

Integrating rainwater-harvesting basins with landscape plantings *throughout* a site's watershed, rather than just at the bottom, is a more efficient and productive approach, since it hydrates the whole site, offsets the need for irrigation, controls downstream flooding and contamination, and utilizes stormwater as an on-site asset rather than a liability. *See the following story for more.*

REAL-LIFE EXAMPLES OF INFILTRATION BASINS

TURNING FLOOD-CONTROL STRUCTURES INTO BEAUTIFUL WATER-HARVESTING AMENITIES— TUCSON, ARIZONA

The 28-home Milagro Cohousing development in Tucson illustrates the effectiveness of integrating infiltration basins throughout a site. There are no conventional detention or retention basins at the bottom of the Milagro development. Instead dozens of small infiltration basins are grouped and scattered throughout the site's landscape. They are the dominant land-form throughout the common area landscape, and in the majority of backyards (figs. 2.23, 2.24).

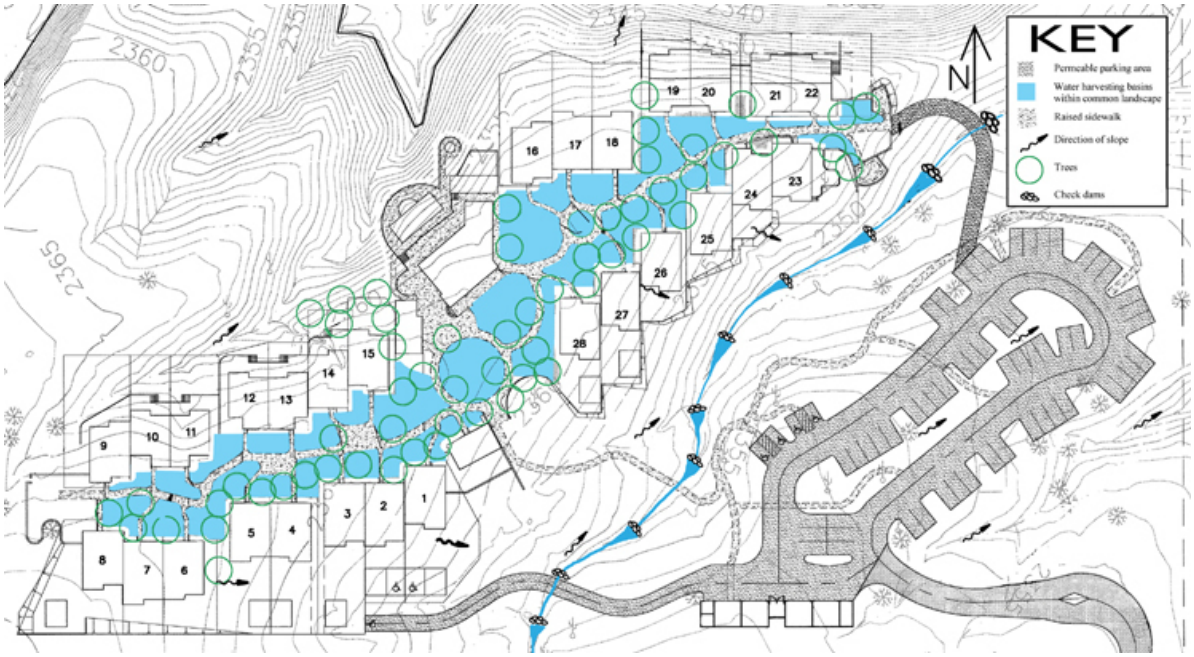


Fig. 2.23. Milagro Cohousing Site Plan. There is no large stormwater-detention/retention basin(s) at the bottom of this site because dozens of small, landscaped, infiltration basins infiltrate and utilize all the runoff beginning at the top, and continuing throughout, the development. Although unmarked, there are also infiltration basins in many residents' back yards. Trees are selected and placed to maintain winter solar access to south-facing windows. Reproduced with permission of Tomas Guido Jr., TnT Engineering

Fig. 2.24A. Rainfall collected in newly constructed infiltration basins minutes after a large summer storm. The basins have not yet been mulched or planted. Milagro Cohousing, Tucson, Arizona. Credit: Natalie Hill.

Fig. 2.24B. Same basins mulched and vegetated. Basins are designed to infiltrate water quickly so there are no problems with mosquitoes or anaerobic soils. These basins, with their spongy mulch and soil-burrowing plant roots, infiltrate all water within 20 minutes. Photo taken November 2004

Fig. 2.24C. Same basins and their thriving vegetation in 2011.

Raised pathways break the landscape into an integrated series of large basins. Small earthen berms divide these large basins into groups of smaller infiltration basins, which hold both the rain that falls within them and roof runoff. Diverse arrays of food-producing, wildlife-attracting plants are planted within the basins to utilize this rainwater. Mulch then covers the soil's surface to make that rainwater go further.

Some homeowners direct their roof runoff to above-ground cisterns first, which then direct their overflow to the basins. The cistern water is then doled out in the dry seasons to irrigate more water-needy plants such as vegetables.

In the unlikely event the basin system overflows, each basin overflows to the next to manage the excess water. The concrete sidewalks of the raised paths act as stabilized spillways between basins and dip slightly where surplus water is meant to pass. The final overflow exits from the lowest basins into a natural drainage, which is alive with undisturbed, established vegetation that is enhanced by a series of small water-harvesting check dams. That rainwater and wastewater alone

are enough to enable the designed landscape to produce 100 pounds (45 kg) of organic produce per resident per year.

This system of infiltration basins holds approximately ten times more stormwater than a conventional system of retention basins, though it does far more than control flooding. By integrating basins throughout the landscape, flood-control strategies double as a passive rainwater-irrigation system that nurtures a community orchard, gardens, native-wildlife habitat, and living air conditioners in the form of shade trees.

Household greywater could also be directed to these basins (as illustrated in chapter 12) to act as a supplemental irrigation source. However, at the time of construction, such a greywater system was not yet legal. (Greywater harvesting is now legal—see chapter 12). So, Milagro treats all its wastewater on site via a constructed wetlands at the bottom of the site, then pumps the water back up to subsurface irrigation lines 8 inches (20 cm) beneath the bottom of the basins. This recycled water is a great boon for the landscape, but it does introduce unwanted salts to the soil, just as greywater would. But the rainwater again saves the day, since it flushes the salts from the root zone of the plants each time it fills the basins.

This system has received a government permit and can be duplicated with help from a progressive civil engineer. David Confer and I designed the layout of basins and landscaping to maximize rainwater use in the landscape, provide shade trees for passive cooling, and maintain winter solar gain for south-facing windows. Civil Engineer Tomas E. Guido Jr. of TnT did the engineering.

For more information visit Milagro's website at MilagroCohousing.org.

PLANTING WATER IN POTS— INDIA AND ARIZONA

The next step beyond planting in bowl-like basins is actually planting pots (fig 2.25). Unglazed, fired earthen pots, or ollas, can be buried to their necks in a planting area (ideally a basin) and filled with clean water (preferably salt-free rainwater from a cistern) to irrigate adjacent plants. If your pot has a drainage hole at the bottom, this can be sealed with silicone caulk (check to make sure it does not leak before you bury it). Once buried, a small plate or flat rock is placed over the pot opening to reduce evaporation, and to prevent mosquito breeding and lizard drownings.

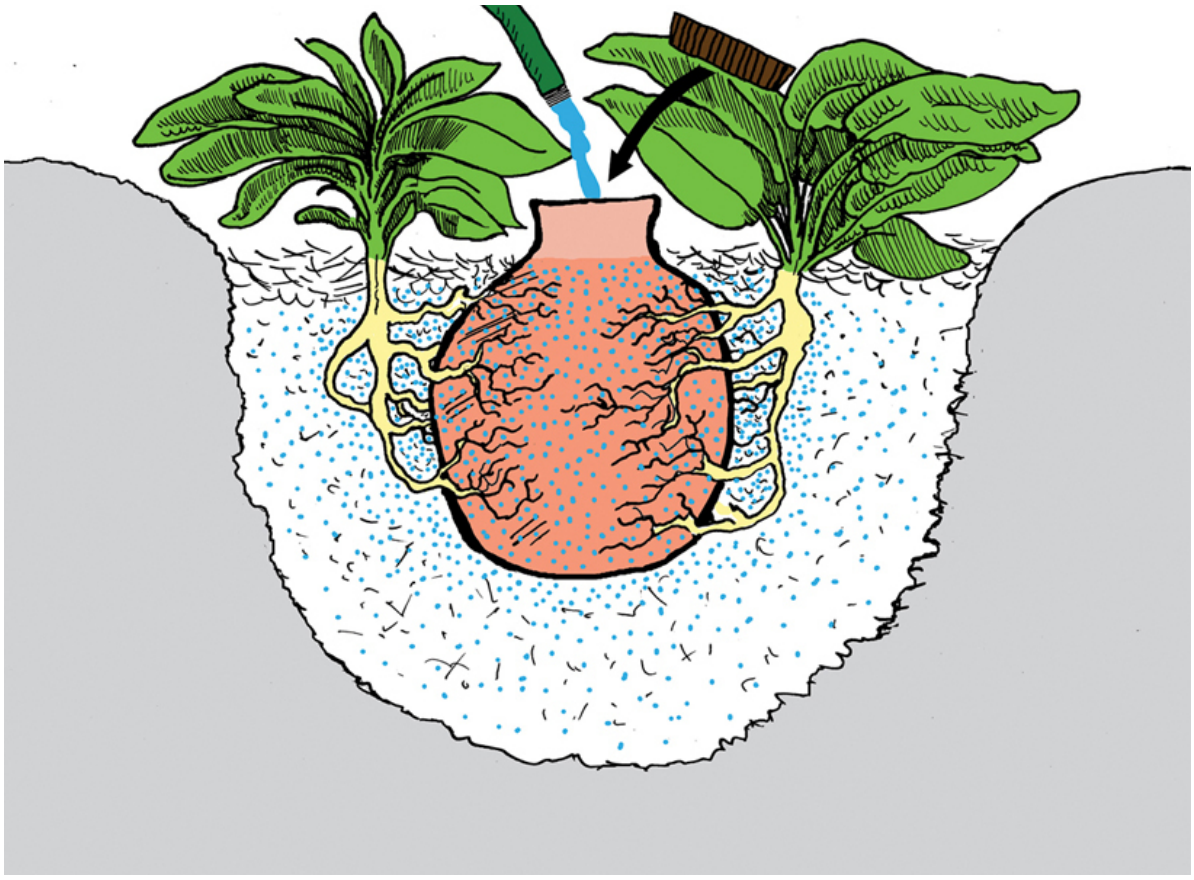


Fig. 2.25. Low-tech subsurface irrigation system of a partially buried clay pot, or *olla*, filled with water

Seeds are planted within an inch or two of the pot where the soil is wetted by the pot. Depending on your soil and seed, you may be able to then water just the pot, or you may need to directly water the soil around the seeds for a couple of weeks until the seedling roots extend to the water slowly wicking through the ceramic walls of the pot. The pot is refilled to the top as needed. Sustainability researcher David A. Bainbridge reports that efficiency of the clay pot method is much better than drip irrigation and as much as ten times more efficient than conventional surface irrigation.[6]

A study in India found this method grew melons and pumpkins to maturity with very little water (less than 2 cm of water over a hectare of land for the entire 88-day growing period).[7] In my Tucson garden, 1.5- to 2-gallon (5.6–7.5-liter) pots irrigating established perennial herbs (oregano, garden sage, chives, marjoram, thyme, fennel, and lemon grass) needed to be refilled twice a week in the summer months and once a week in winter.

INFILTRATION BASINS PRODUCE ABUNDANCE IN A COMMUNITY GARDEN—DOWNTOWN TUCSON, ARIZONA

Within inner-city Tucson, Arizona, water-harvesting infiltration basins are pumping out produce where there was once a parking lot. It all started in 1998 when neighborhood volunteers reclaimed an abandoned softball-field-turned-dirt-parking-lot and created the Dunbar/Spring Organic Community Garden. Grant money paid for a 3-foot (1-m) high fence to keep dogs and cars out of the area, and neighborhood volunteers drew up plans for garden plots, an orchard, a shade ramada and tool shed, a playground area, and a mini-ethnobotanical park of native vegetation.

Infiltration basins were dug to create all the planting areas. The sunken garden beds were dug by hand to forever connect the community volunteers to the garden via their sweat and effort, and to spread the hands-on knowledge of how to create such basins. Upon completion, the top of the sunken beds' prepared soil was about 6 inches (15 cm) below grade. Basins for the orchard and mini-ethnobotanical park were dug 18 to 24 inches (45 cm to 60 cm) deep with a donated backhoe and operator from Tucson Water. Winding, raised pathways were created from the excavated dirt to access the plantings and shed runoff to the vegetation (figs. 2.26A, B and 2.27).

Fig. 2.26A. Garden site fenced and ready for digging

Fig. 2.26B. Volunteers digging sunken garden beds in 1998

Three raised garden beds were also built to act as benches and provide easy gardening for people unable to bend over. Yet it was soon discovered that the raised beds dried out more quickly than the sunken beds. So, even the older and less able gardeners now typically choose to garden in the sunken beds over the raised ones.

The success of the infiltration basins was apparent even before the garden was finished. Just after the basins were dug, but before they were planted or mulched, summer storms dumped 2 inches (51 mm) of rain on them within a few hours. The basins captured all the rainfall and on-site runoff, while the raised dirt paths remained firm and dry enough for wheelchair and wheelbarrow access (fig. 2.27).

Fig. 2.27. Recently completed sunken garden beds minutes after a downpour. Summer 1998

It took two days for the collected water to infiltrate into the soil or evaporate into the air. Then seeds and plants were put into the moist earth, and a layer of mulch (compost, aged manure, straw, and salvaged woodchips) was spread over all the basins but not tilled in. More mulch accumulated as gardeners allowed

falling leaves to remain in the basins. Prunings were cut up on site to 4-inch (10-cm) lengths, and laid beneath the plants.

The following year summer storms again dropped 2 inches of rain within several hours. As before, the basins harvested all runoff. But this time—thanks to the mulch, vegetation, and a booming earthworm population—the harvested water infiltrated into the soil in 20 minutes, as opposed to two days. Far less was lost to evaporation this time. And mosquitoes were never an issue, because the water was in the soil and plants, not on the surface.

The garden is watered by rain (averaging 12 inches or 305 mm per year) and an automatic drip-irrigation system hooked up to the municipal water supply. A rain sensor is connected to the irrigation timer and shuts the system off when it rains and does not turn it back on until the soil begins to dry. Thanks to the basins and mulch, the garden's irrigation system can remain off for up to two weeks at a time. That saves thousands of gallons of groundwater annually and helps reduce damaging salt buildup from the application of salt-containing municipal water.

To save even more water, the timer is set to come on only at night or very early in the morning when evaporation rates are lower. The timer is also manually reset with the seasons, watering far less in the cooler months, then increasing waterings in the hot dry months. All these strategies cost little or no money, save water and maintenance, and best of all, they help produce an abundance of tasty organic fruits and vegetables in a beautiful garden (fig. 2.28).[8]

Fig. 2.28. The garden in winter 2005

RAIN GARDENS—THE INFILTRATION BASINS OF WETTER LANDS

Rain gardens are popping up all over wetter states such as Maryland, Virginia, Wisconsin, Michigan, and Minnesota, and in the Northwest U.S., as a positive response to growing problems of groundwater depletion and water pollution. They are basically water-harvesting infiltration basins planted with colorful shows of flowering native vegetation, and some add artful downspouts and sculpture to celebrate the rain and its harvest (figs. 2.29 - 2.31). They replenish or recharge near-surface groundwater supplies with rain that would otherwise run off paved, compacted, or convex surfaces. In addition, rain gardens using hardy native vegetation improve water quality by eschewing chemical pesticides and fertilizers, while using the plants, mulch, and microorganisms to naturally filter pollutants carried in the captured runoff.

Fig. 2.29. Celebrate the rain! Roof runoff from the New Seasons Market showers down from a cloudlike downspout onto a sculpted figure within a rain garden. As the falling water hits and moves the figure's propeller umbrella, the figure also starts to move and dance in the rain. Portland, Oregon

Search "Water-Harvesting Art" at HarvestingRainwater.com for more.

Fig. 2.30. Celebrate the rain! Steelhead trout swim up a steel downspout directing roof runoff to a rain garden below. Portland, Oregon.

Fig. 2.31A. Metal salmon swimming up downspout flow. Portland, Oregon

Fig. 2.31B. Downspout salmon, green roof, and ground-level rain garden

Every year
billions of gallons of stormwater
runoff from rooftops and parking lots gets mixed
with sewage and pours into the Willamette River through
Portland's combined sewage system. Many Portland homeowners
are helping to reduce these overflows by disconnecting their
downspouts from the sewer system.
The rooftop garden above the entry vestibule is the highlight of our
sustainable approach to rain water collection on this property. Water
from the upper roof is diverted to the lower roof by 3 large steel
downspouts. The water then splashes over the leaping salmon and
down to the garden. The plant and soil material in the garden acts
as a natural filter and water detention system. Any water that isn't
absorbed in the garden is distributed throughout the property in
the planted swales. The result of this innovative system is that no
stormwater runoff from this property goes into the
combined sewer system.
Thank you to Ivan McLean, the sculptor
who created the leaping
salmon.

Fig. 2.31C. Wall plaque describing the benefits of the site's rain gardens

Rain gardens are a wonderful yard-scale strategy for irrigating landscapes naturally and cleaning up watersheds locally. As RainGardens.org states, "Government studies have shown that up to 70% of the pollution inour streams, rivers, and lakes is carried there by storm-water. Although most people never think about storm-water, about half the pollution that stormwater carries comes from things we do in our yards and gardens!"[9]

There are many great resources on rain gardens, with more appearing all the time. I invite you to plug "rain gardens" into a web search. Look for resources applicable to your area and ecosystem, since most offer plant lists and planting instructions for specific climates and regions (primarily non-dryland).

Search "Multi-Use Rain-Garden Plant Lists" at HarvestingRainwater.com for dryland-specific plant lists.

Fig. 2.32. Flow-through rain gardens bring life a very urban context, receiving driveway and road runoff at Dolph Creek townhomes, Portland, Oregon.

Fig. 2.33. Once buried and paved over, now daylighted, headwaters of Dolph Creek doubling as a backyard forest and rain garden for roof runoff at Dolph Creek townhomes and apartments. Portland, Oregon. Search "Daylighting" at HarvestingRainwater.com for more

CHAPTER 3

Berm ‘n Basins

Berm ’n basins simply cast a net across slopes to catch runoff and encourage it to infiltrate into the soil to grow soil-stabilizing and erosion-checking vegetation (fig. 3.1, box 3.1). There are many variations of this strategy and you can tweak their placement and use to make more. In this chapter you’ll see how potted plants set along a contour line have created a water-harvesting plant nursery on a sloped lot, how smile-shaped berms are boosting the growth of trees beside which they are placed, and how a net and pan system of berms has harvested enough rainwater to grow fruit trees in the Negev desert on just 4.1 inches (104 mm) of annual rainfall. You’ll also see how raised paths and roads built on contour become water-harvesting strategies, how burned trees felled on contour are helping rehydrate and revegetate burned forests, and how the berm ’n basin concept can be suited and oriented to the wind to harvest windblown snow.

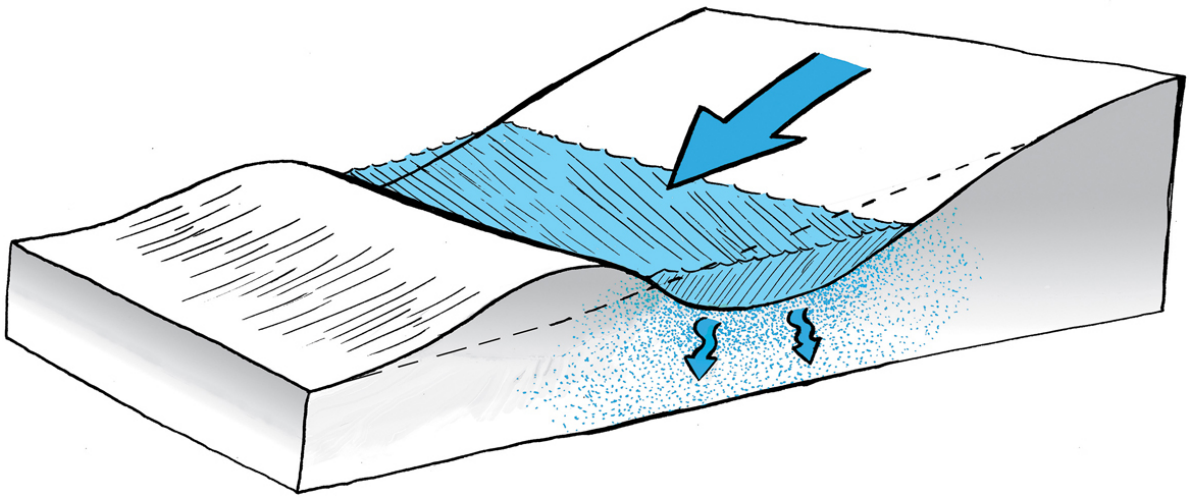


Fig. 3.1. A berm ‘n basin holding runoff water and infiltrating it into the soil

Box 3.1. Berm 'n Basin Synonyms, Terminology

Within the permaculture community,[1] what I call a "berm 'n basin" is known as a "swale" cut on contour. Outside the permaculture community, the term "swale" usually refers to a gradual drainageway cut off contour. Confusion is common. So I use "berm 'n basin" as a general term for contour swales and similar earthworks that stop and infiltrate runoff. I use the term "diversion swale" for a gradually draining swale. It's my hope these terms will be more readily understood by all.

WHAT IS A BERM 'N BASIN?

The berm 'n basin (b'nb) creates a net that is perpendicular to sloping land in order to *slow*, *spread*, and *infiltrate* runoff that would otherwise flow unchecked downhill (fig. 3.1). Thus the b'nb helps accumulate resources (water, soil, seeds, organic matter) where they would otherwise readily and erosively drain away. A b'nb usually consists of two parts: an excavated basin and a raised berm located just downslope of the basin. The berm can be made of the earth excavated to form the basin or it can be made from brush, rock, or additional earth. The basin holds water; adding the berm enables you to harvest even more water. This water then grows soil-stabilizing, resource-producing vegetation to maximize living and organic groundcover.

Berm 'n basins only work on slopes—not flat ground. Also berm 'n basins generally have a sloped basin, as a level-bottomed basin would mean more earth moving than necessary on a slope.

The berm can wind serpentine-like along a contour line, catching and infiltrating runoff all along its length; it can be made boomerang-like to focus its harvested water around select plantings; or it can literally look like a net of berms draped around an orchard of trees—each tree placed within a different square of the rain-catching net (fig. 3.2 shows two variations). In many instances the berm, or a section of it, can double as a raised path.

Fig. 3.2. Boomerang berms to focus water around trees and contour berms below on hillsides

Other earthworks may be used above or below berm ’n basins depending on the landform of the watershed. Study your watershed, and start at the top with the appropriate strategy. The b’nb strategy and its variations is just one of your options.

See appendix 4 for more resources related to berm-’n-basin-type earthworks and their use in permaculture and other contexts.

WHERE IS A BERM 'N BASIN USED?

Berm ’n basins are used across gently- to moderately-sloped land where they intercept and infiltrate runoff water into the soil. This technique should never be used in or across drainages. B’nbs are generally used on slopes with less than 3:1 pitch, where for every three units of horizontal length, a slope drops less than one unit in height.

Earthworks on steeper slopes (of 3:1 or more) will most likely need the stabilization of a retaining wall (see chapter 4 on terraces). Fig. 3.3 illustrates different slopes and different berm 'n basin and terrace options.

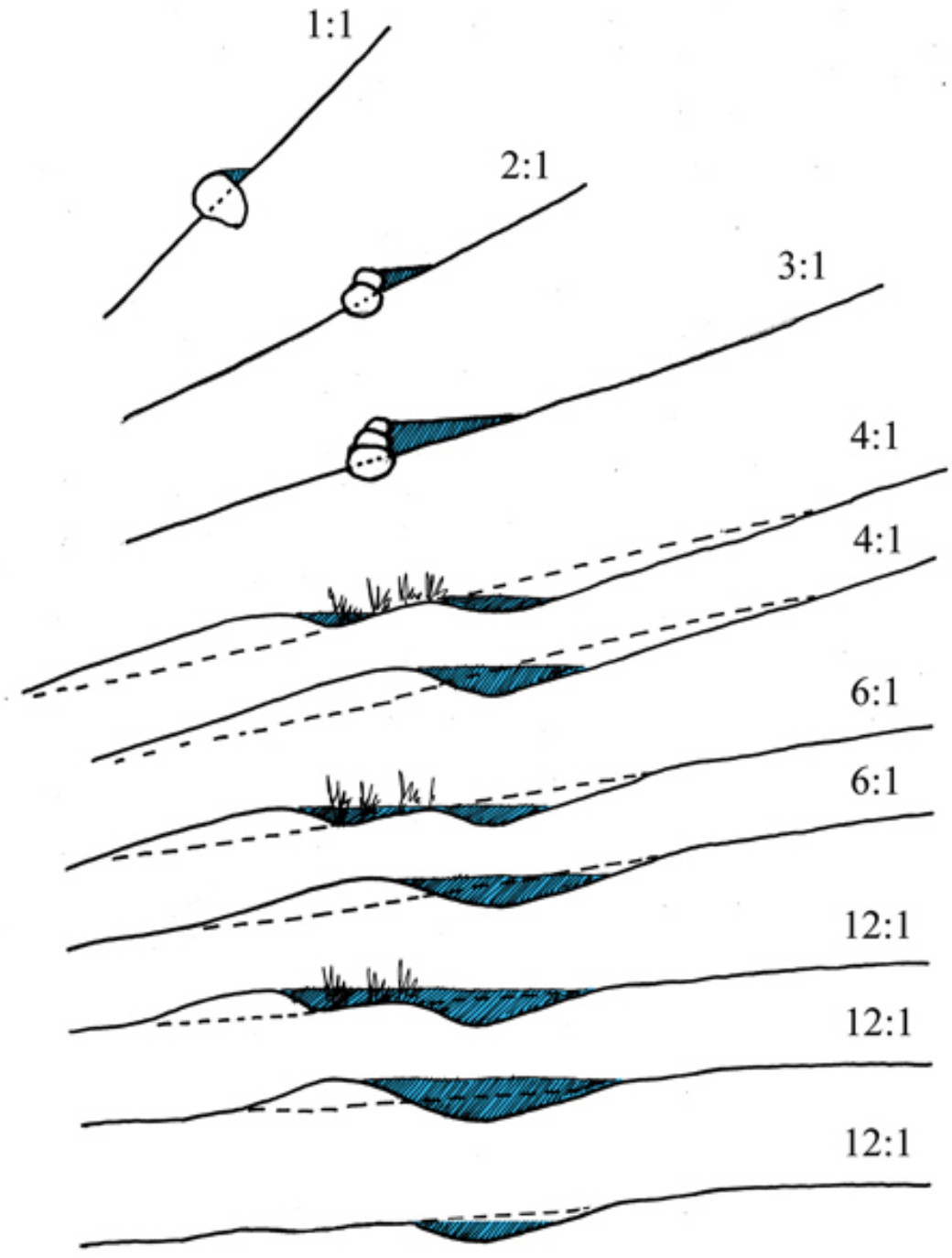


Fig. 3.3. Berm 'n basins and terraces with stone retaining walls at varying slopes. Dotted lines indicate original grade. Shaded areas indicate water-holding capacity of berm 'n basins, and soil-holding capacity of terraces. Note

how steepness of slope affects capacity. With the slopes showing berm 'n basins, note the options of one large deep basin versus two shallower basins made by placing the berm farther downslope to leave a strip of undisturbed and vegetated soil between berm and basin. The sides of the berms and basins themselves are constructed so they do not slope more steeply than 2:1. Terraces are appropriate for slopes 3:1 or greater. Bottom example is bermless

The basins of b'nbs can quickly fill with sediment and loose their capacity and effectiveness in sparsely vegetated areas that have high sediment volumes in storm runoff. So in these contexts, contour plantings, contour rock berms, or sheet flow spreaders (chapter 10) may be a better option since they are designed to harvest both water and sediment.

TOOLS AND MATERIALS

Siting tools: a bunyip water level, A-frame level (appendix 1 in this volume gives instructions for both these homemade levels), laser level, or transit.

Excavation tools: pointed shovel, pick, and rake. Optional equipment for larger jobs can include a Ditch Witch (gas powered ditch digger) operated by one person walking and wrestling behind it, backhoes, bulldozers with a six-way blade, or earth graders in areas where the topography is not irregular or too steep.

Construction materials: Try to responsibly use materials at hand rather than purchasing them. Berms can be made of soil, stone, brush, logs, living vegetation, and/or other nontoxic local materials.

STEPS TO BUILD A BERM 'N BASIN

SITING

Assess the slope, water flow, and potential for various water-harvesting strategies throughout your site. Note if and where a berm 'n basin would be appropriate to meet your site needs, and which variation. Take into account the land slope and the condition of the watershed. On steep overgrazed or disturbed land, you will be confronted with large volumes of fast-moving sediment-laden water in intense rainfalls. To manage this water, successive lines of berm 'n basins may be needed, placed at close intervals going down the slope. On gentle slopes covered with thick native grass, the watershed can absorb more rainfall before significant runoff begins, so fewer, more widely spaced berm 'n basins may be sufficient, or use none at all, avoiding disturbance to the intact fabric of the land. Remember the

important principle of harvesting water: *Start at the top of the watershed, or as close to the top as you have control over, and work your way down*. If other water-harvesting strategies are better suited above the area where you want to make berm 'n basins—start with the upper area, then make your b'nbs below if still needed.

Use a bunyip water level, laser-level, or A-frame level to work your way along the contour of the land, staking the location of the berm 'n basin to ensure it will hold runoff water rather than drain it. Mark your berm locations with stakes, flagging, surveyor's spray paint, or a line scratched deeply into soil (fig. 3.4A shows identifying the contour line; fig. 3.4B shows digging along the contour line).

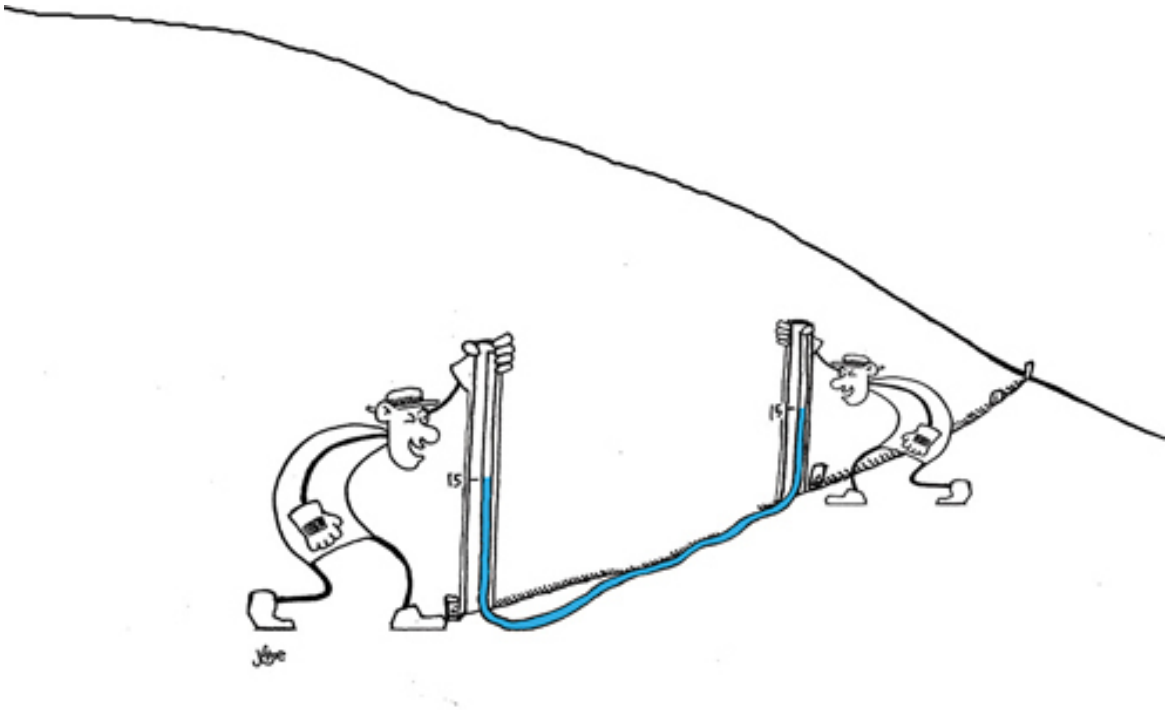


Fig. 3.4A. A contour line identified using a bunyip water level is marked with stakes and a line scratched into the soil to show where to construct a contour berm

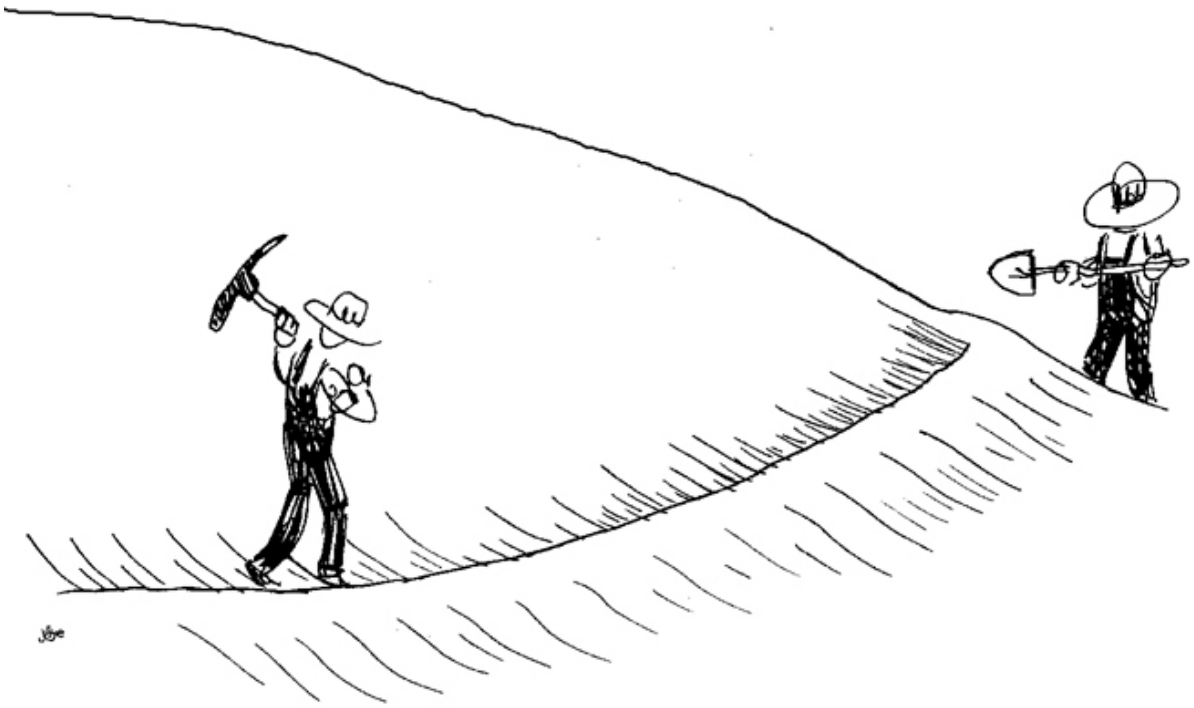


Fig. 3.4B. Digging of the berm 'n basin along the contour line

Mark on site all the potential berm 'n basins you plan to build *now* to integrate them with one another. For example, through integration you can ensure that each earthwork overflows to the next below, berms are laid out where you need raised paths. You can adjust the curves of the berms or the distance between berms so all elements look and function well. On-site markings enable you to see and make needed changes to b'nb placement based on how each b'nb relates to other on-site elements such as fence lines, vegetation, pathways, etc. However, consult your site plan to make sure your b'nb placement also works with planned future plantings or other design elements.

Carefully recheck layout and markings *before* you move any earth, since your markings are much easier to change than constructed berm 'n basins. If you hire an equipment operator, complete all preparation work beforehand so s/he doesn't sit around charging you while you scramble to mark the work site.

APPROPRIATE SIZE

Figs. 3.5 A and B for berm 'n basins, along with terms used for their various components.

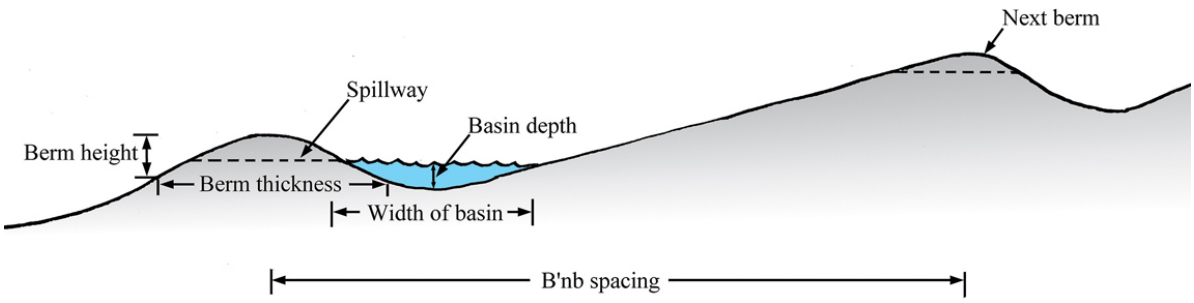


Fig. 3.5A. Cut-away (side) view of berm 'n basin, with measurements

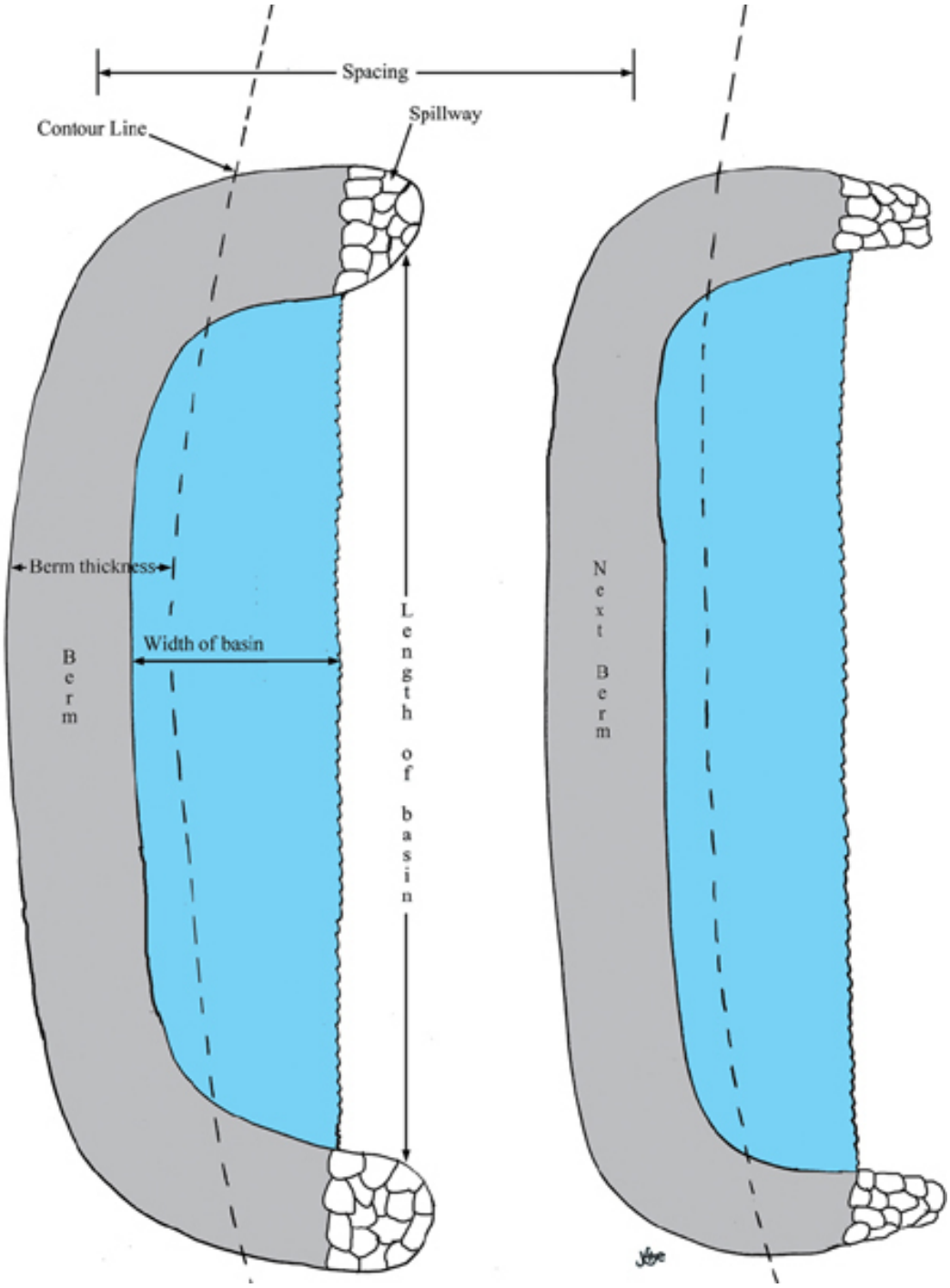


Fig. 3.5B. Overhead (top) view of berm 'n basin

Berms

Make bigger berms than you need rather than smaller ones. You'll reduce the chance of a berm blowing out (being breached) in a big storm or eroding too quickly. As a rule of thumb, make the base of the berm portion of your b'nb

structure at least four times as thick or wide as the height of the b'nb, measured from the bottom of the basin to the top of the berm (fig. 3.6). This will give you a berm with a 2:1 slope, though a more gradual slope of 3:1 will create a still more stable berm.

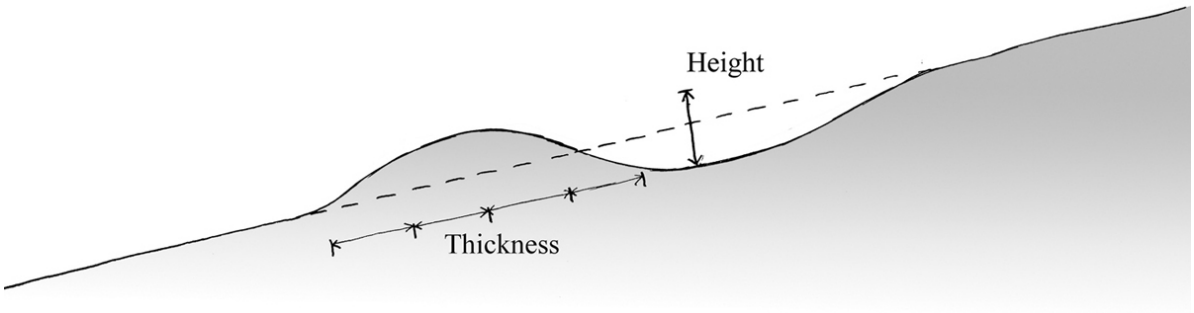


Fig. 3.6. Recommended minimum thickness:height ratio of a berm is 4:1

For example, the berm portion of a 12-inch (30-cm) tall dirt b'nb would be about 4 feet (122 cm) thick at its base. This also gives your berm 'n basins a gradual slope, reducing tripping hazards. The distance from the bottom of the basin to the top of the berm (its height) typically ranges from 12 inches (30 cm) to 3 feet (0.9 m).

In sandy soil, make berms thicker. In clayey soil you can make berms a bit higher and narrower because this soil generally holds together well. In gopher country, regardless of soil type, always go thicker so critter holes will be less likely to blow out the berms. And berms should always be wider/thicker where they double as raised accessways such as foot and wheelbarrow paths (3-6 feet or 0.9-1.8 m; fig. 3.7), a tractor trail (8 feet or 2.4 m), or driveway (slightly wider than vehicle).

Fig. 3.7. Raised path with rock-stabilized edges, Lady Bird Johnson Wildflower Center, Austin, Texas

Berm spillways will be discussed later. Spillways are indented about 1/2 down from the top of the berm.

Basins

When you dig a basin on a slope, it will generally be shaped like a rounded upside-down triangle (fig. 3.5A) with the rounded "point" of the triangle at the bottom of the basin. Its *length* is the distance that the b'nb runs along the land contour; its *width* is determined by finding a *level* line from the top of the berm's spillway to the back of the basin's slope. *Depth* is the vertical distance from the bottom of the basin to the top of the berm's spillway (fig. 3.5A). For specific calculations determining b'nb water-storage capacity see box 3.2.

Box 3.2. Calculating Approximate Water-Holding Capacity or Volume of Berm 'n Basins

A. MAXIMUM B'NB CAPACITY

To calculate the maximum volume of water your berm 'n basins could hold at one time, you will need to know the depth, width, and length of your b'nb.

- **Depth** is the vertical distance from the bottom of the basin to the top of the berm's spillway.
- **Width** is the horizontal distance from the top of the lip of the berm's spillway to the poi upslope where water will back up to.
- **Length** is the distance that the b'nb runs along the land contour.

Figs. 3.5, 3.8, and 3.9 show where depth, width, and length measurements are taken; figs. 3.8 and 3.9 show dimensions for an example b'nb. Since the water will be held within a rounded triangular space (in cross-section view, as in fig. 3.5A) rather than a rectangular space, you will use the equation for the area of a triangle, which in this case is:

$$\text{AREA} = 1/2 \times \text{WIDTH} \times \text{DEPTH}$$

$$\text{VOLUME OF WATER-HOLDING CAPACITY} = \text{AREA} \times \text{LENGTH}$$

$$\text{VOLUME} = 1/2 \times \text{WIDTH} \times \text{DEPTH} \times \text{LENGTH}$$

Plugging in the numbers from our example berm 'n basin:

$$\text{Volume in cubic feet} = 0.5 \times 10 \text{ ft} \times 2 \text{ ft} \times 40 \text{ ft} = 400 \text{ ft}^3$$

Multiply the 400 ft^3 volume by 7.48 gal/ft^3 to convert to gallons:

$$\text{Volume in gallons} = 400 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 2{,}992 \text{ gallons}$$

That's a lot of water for one small b'nb! And it's much cheaper to build than a tank that holds the same volume.

B. B'NB CAPACITY PER FOOT OF LENGTH

You can also calculate the water-holding capacity for each 1 foot length of b'nb instead of for a specific length:

$$\text{Volume in cubic feet per 1 foot of berm} = 0.5 \times 10 \text{ ft} \times 2 \text{ ft} \times 1 \text{ ft length} = 10 \text{ ft}^3 \text{ per foot of length}$$

Again, to get gallons, multiply by 7.48 gal/ft^3

$$\text{Volume in gallons} = 10 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 74.8 \text{ gal/per foot length of b'nb}$$

Note that these calculations do not take into account any water infiltrating into the soil, only water collected on the surface, and runoff from upslope.

See Equations 10B and 11B in appendix 2 for these calculations and examples in metric units.

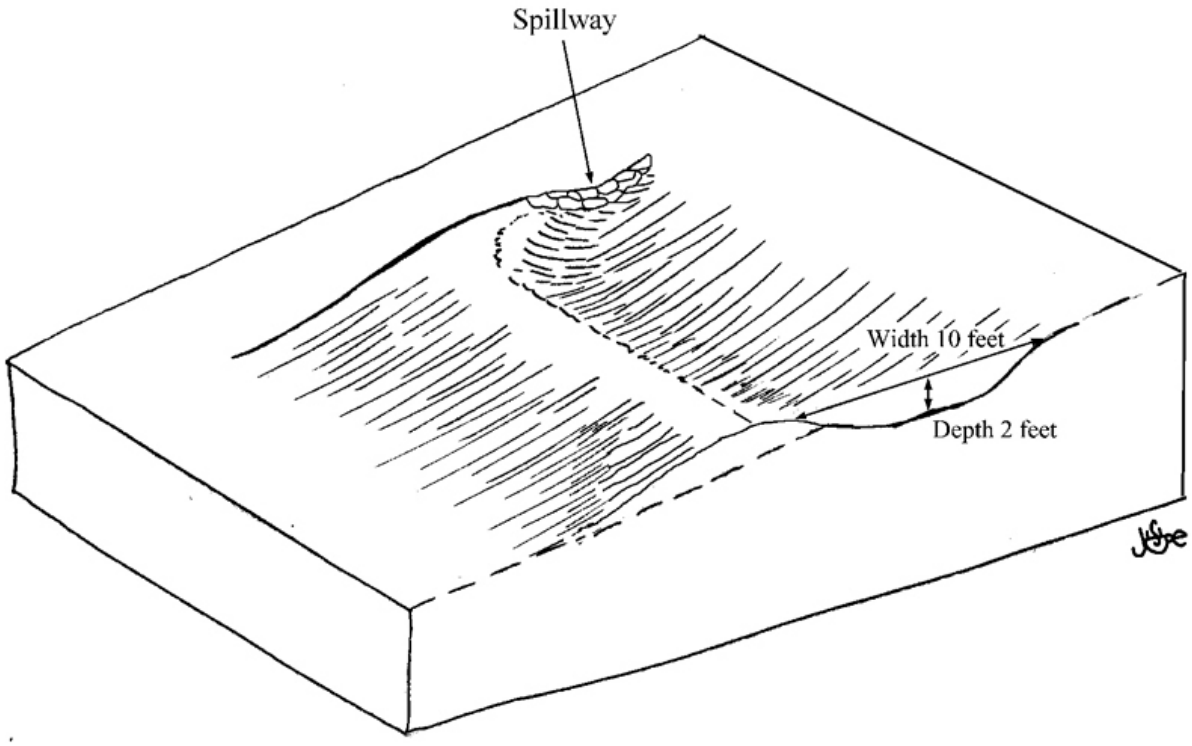


Fig. 3.8. Cross section showing depth and width measurement locations; the depth is 2 feet and the width is 10 feet.

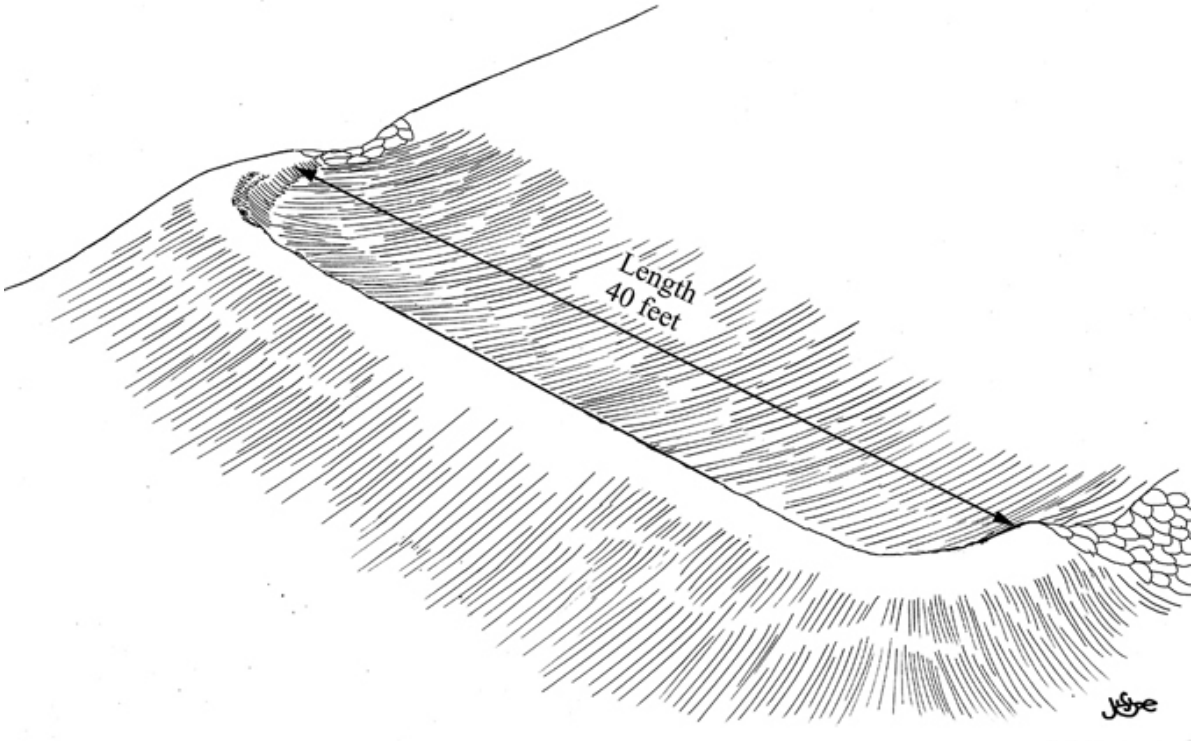


Fig. 3.9. Perspective view showing length measurement; the length is 40 feet.

Ideally, the finished "footprint" of a b'nb should eventually be sheltered by the vegetation growing on/within it or canopying over it. The vegetation shelters the berm 'n basin, increases water infiltration, and decreases soil moisture loss to evaporation.

SPACING

The berm 'n basin is a localized area where a certain volume of water can be caught to be infiltrated into the earth. But, while some of that water is the rain that falls directly on the b'nb, most of the harvested water is from a much larger area, a subwatershed determined by b'nb *spacing*.

Base the berm 'n basin size and spacing on your site goals and rainfall and runoff conditions. You can harvest the same amount of water by building many small b'nbs close together or building two large b'nbs far apart. In the first case, a little bit of water will infiltrate in lots of places throughout your landscape; in the second case, a lot of water will infiltrate in just two places in the landscape. If you want to cover a slope with drought-tolerant plants for erosion control, build many small b'nbs to serve vegetation planted throughout your landscape. If you want to grow water-hungry fruit trees in the desert, you could build two large b'nbs and plant climate-appropriate fruit trees along them to get a greater concentration of water.

Space berm 'n basins according to their water-holding capacity and the expected volume of runoff. The lower the water-holding capacity of the b'nb, and the greater the volume of expected runoff, the closer together b'nbs should be, resulting in a smaller "microwatershed" serving each. The greater the water-holding capacity of the b'nb and the lower the volume of expected runoff, the farther apart berm 'n basins should be, so a larger microwatershed serves each one. Generally, place and size your structures to hold all the runoff that will drain into them in a typical large storm. In Tucson, at a minimum I strive to hold all the runoff from a very large, 2-inch (51-mm) rainfall. But holding all the runoff from a much less frequent 3-inch (76-mm) storm is preferable, and hydrates the landscape even more.

You don't have to build all your berm 'n basins at once. Start with one at the top of your site and add more downslope as you are able. See how the first one performs in a storm. How might you refine your approach? If so much water overflows your berm 'n basin that your berm is eroding away or blown out, make

your b'nb bigger or build future ones closer together. If little or no water backs up behind your berm 'n basin, you can probably build future ones smaller and space them farther apart.

As you gain experience, the size and spacing of your berm 'n basins and other water-harvesting earthworks will become more intuitive. For specific calculations to determine spacing of b'nbs, see box 3.3. Appendix 2 includes additional handy calculations for catchment area, sizing, runoff, and others.

Box 3.3. Calculating Berm 'n Basin Spacing Distance

To figure out the spacing distance between b'nbs, i.e., the distance between one berm and the next berm above it (see fig. 3.5), you need to know the typical percentage of total rainwater that will run off a slope. This is known as the runoff coefficient. The runoff coefficient for any given slope depends on what the surface is composed of and whether it has vegetation. Here are suggested *runoff coefficients* for different surfaces expressed as decimals (for example, a runoff coefficient of 85% is equal to 0.85 when expressed as a decimal). Runoff coefficients will be lower for light rains and higher for heavy rains:

- Impervious paving or a building's roof: range 0.85–0.95
- Healthy Sonoran Desert Uplands: range 0.20–0.70, average 0.30–0.50
- Bare earth: range 0.20–0.75, average 0.35–0.55
- Grass/lawn: range 0.05–0.35, average 0.10–0.25
- For gravel, use the coefficient of the ground below the gravel.

The runoff coefficient is greatly influenced by soil type, so there is a broad range of potential runoff values. Large-grained sandy soils have lower runoff coefficients, while fine-grained clayey soils have higher runoff coefficients.

Now, we'll figure out how far apart to put b'nbs. The example site has bare earth with clayey soils, so we'll use the high end of the average runoff coefficient for bare earth, 0.55. We want to harvest most of the rainfall runoff from a large storm; in Tucson, Arizona, this is a 2-inch rainfall event. We want rainfall to be expressed in units of feet instead of inches, so:

2 inches ÷ by 12 inches/foot = 0.17 feet of rainfall.

Then, we use the water-holding capacity of the b'nb calculated in box 3.2 (section B), expressed in units of cubic feet of volume *per linear foot* of berm 'n basin (this was 10 ft^3 per foot of length).

Now, to figure out the spacing distance between b'nbs:

SPACING DISTANCE = B'NB WATER-HOLDING CAPACITY (per unit length) ÷ (RUNOFF COEFFICIENT X RAINFALL FROM A LARGE STORM)

Plugging in the numbers of our example above:

Spacing distance = (10 ft^3 / 1 ft length of b'nb) ÷ (0.55 X 0.17 ft) = 106 ft spacing

This means if you construct your b'nbs about 100 feet apart on the landscape, you will capture most of the rainfall runoff from a large storm in Tucson, Arizona, most of the time (see fig. 3.10).

To capture all of the water from even huge rainfalls in Tucson, we use the highest runoff coefficient for bare dirt, 0.75, and use a rainfall of 3 inches, or 0.25 feet (the chance of a 3-inch rainstorm happening in any given year in Tucson is 1 in a 100) and calculate spacing distance:

Spacing distance = (10 ft^3 / 1 ft length of b'nb) ÷ (0.75 X 0.25 ft) = 53 ft spacing

So b'nbs spaced about 50 feet apart in Tucson would catch every drop of runoff water in a rain event not exceeding 3 inches of precipitation. Remember b'nbs *collect silt and detritus over time*, plus they lose some volume when mulch is thick, so always err on the side of making b'nbs closer together and larger.

See Equation 12B in appendix 2 for this calculation and an example in metric units.

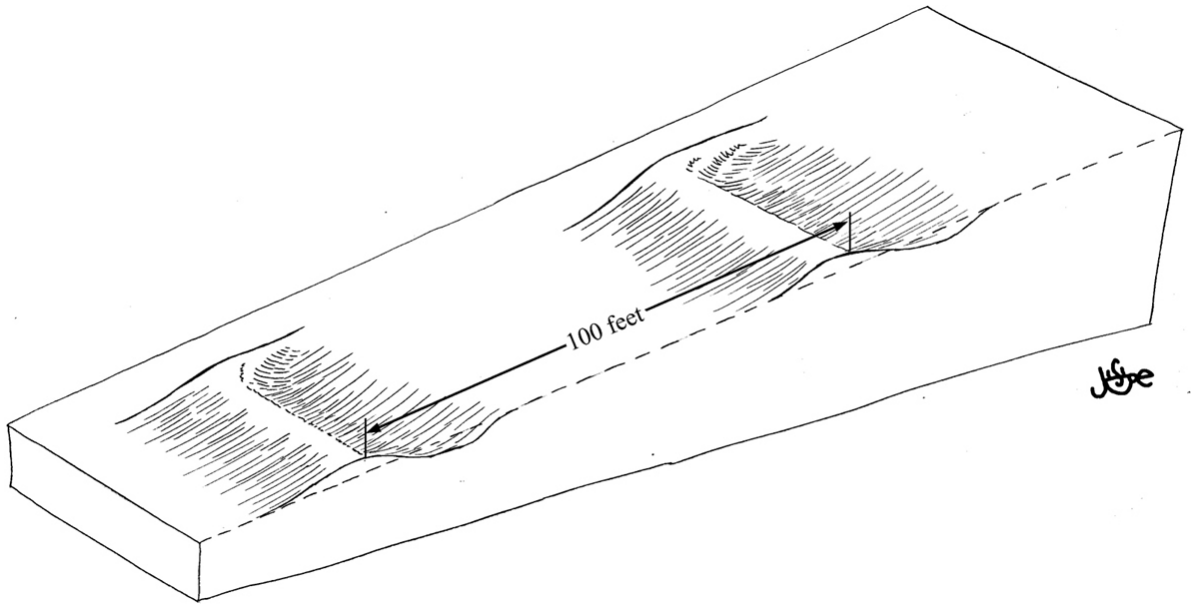


Fig. 3.10. Berm 'n basins 100 feet apart. Not to scale

CONSTRUCTION

To construct a b'nb, dig a basin just upslope from where you marked its location, then use the excavated dirt to build your dirt berm downslope (fig. 3.11). When digging basins, leave established shrubs and trees in place by digging around them—you want to encourage that vegetation. It doesn't matter if the basin's bottom undulates or is a bit irregular; it is the top of the berm that needs to be level. When building up the berm, go ahead and pile the dirt around smaller existing plants along your marked line. But try not to cover the base of larger trees and shrubs since the soil against the trunk may harm them.

Fig. 3.11. Contour berm dug with rototiller, with dirt from basin becoming the downslope berm. Credit: Tim Murphy

Hastening revegetation

If working in a well-vegetated area, you can speed up revegetation of the land you disturb with three methods I learned from Dan and Karen Howell of the Running Rain Society:

1. Leave a 1-foot (30-cm) wide undisturbed vegetated strip of land between each berm and basin (figs 3.12A, B).

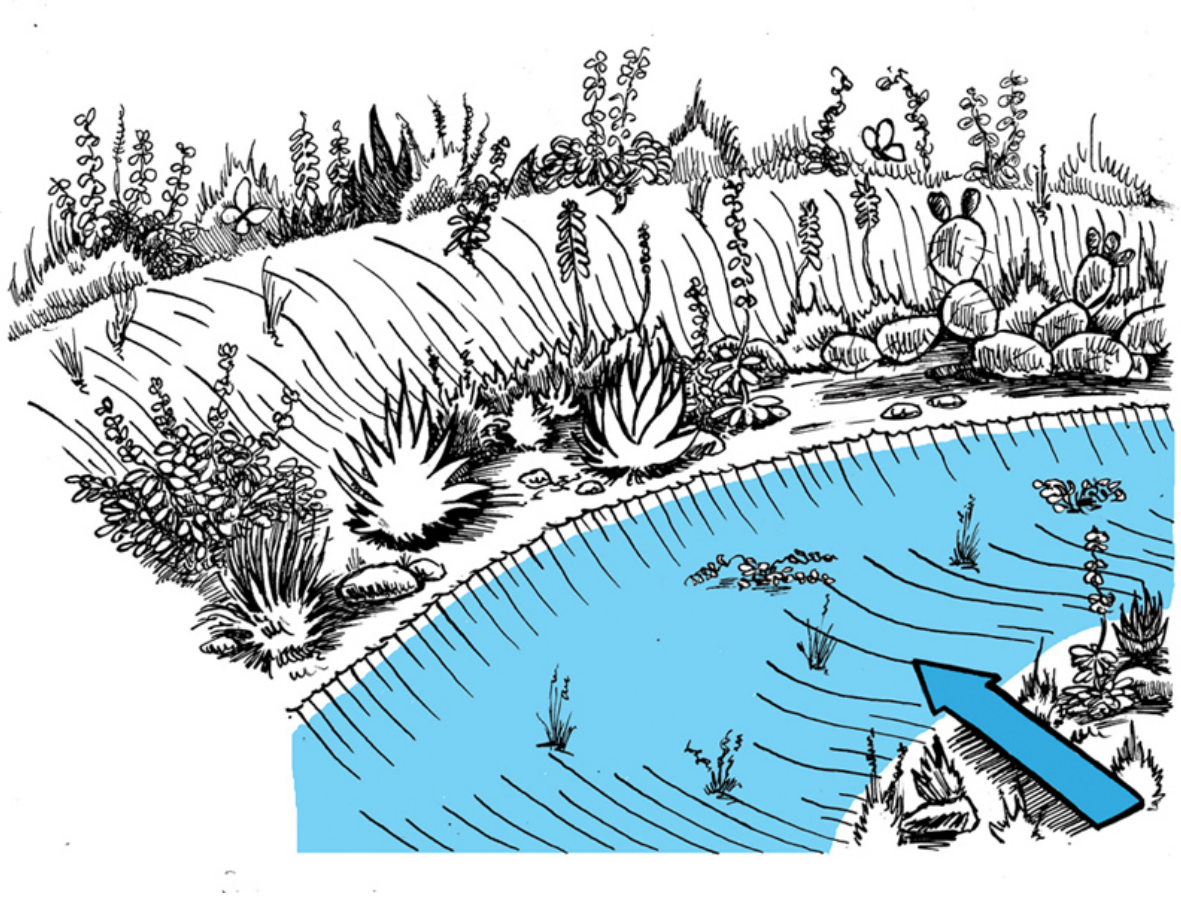


Fig. 3.12A. Speeding up revegetation of earthworks by leaving a strip of undisturbed soil and vegetation between berm and basin

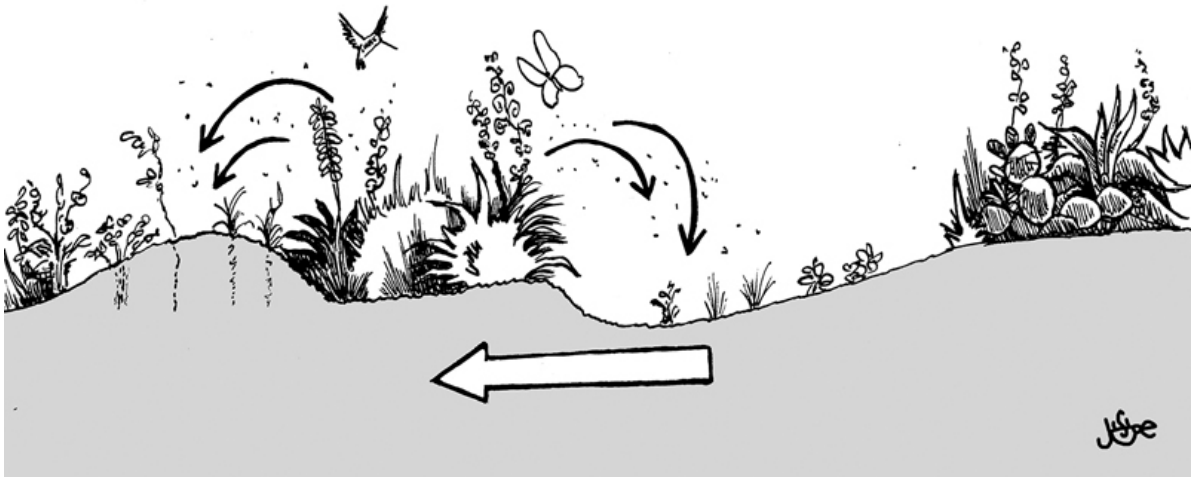


Fig. 3.12B. The vegetation in the undisturbed strips will seed the adjacent bare areas.

2. Break up the basin into a series of smaller basins separated by undisturbed, vegetated strips of land (fig. 3.13).

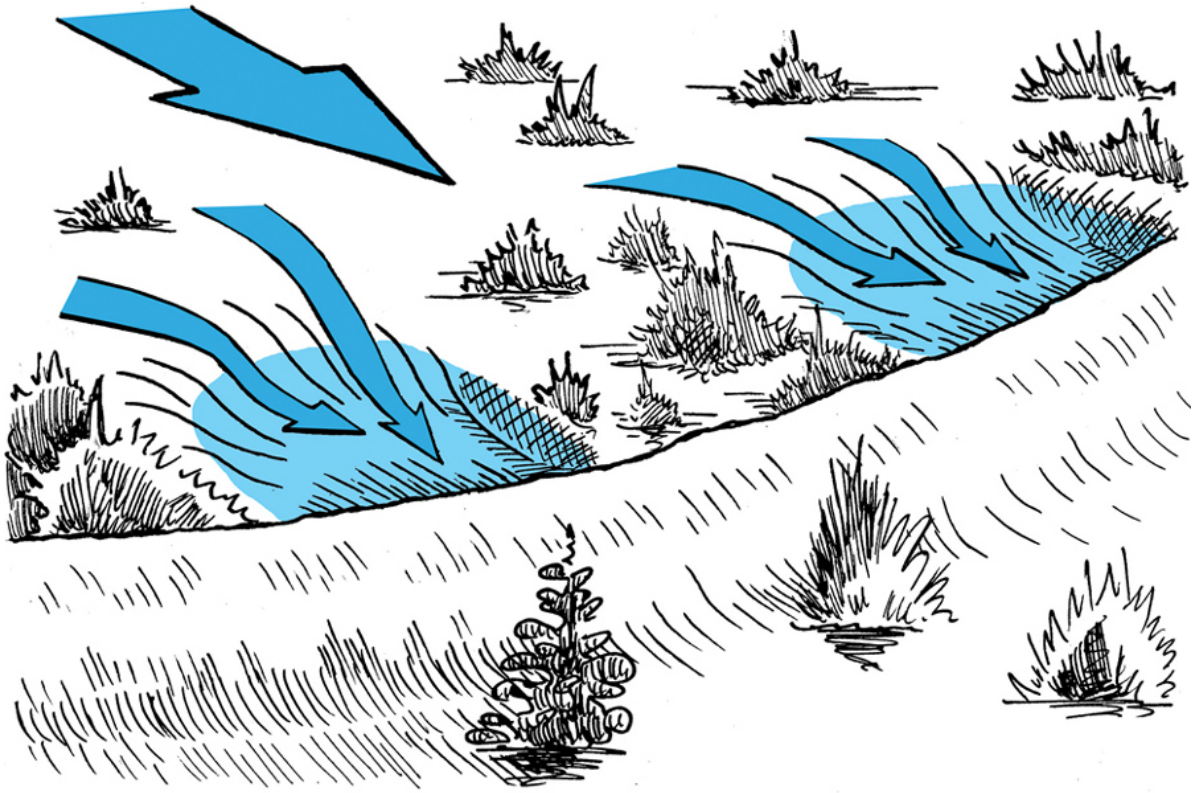


Fig. 3.13. Speeding up revegetation of earthworks by leaving a strip of undisturbed soil and vegetation *between sections* of basin, in effect creating smaller basins

3. Bring in soil to create berms without digging basins. This method works especia well in landscapes with established vegetation, so you don't disturb plant roots v digging.

With these methods the established plants will cast seed and provide some shelter over the newly dug or deposited earth.

Level and tamp your berms

Make the top of the berm level so you won't have any unplanned low points that become unexpected erosive spillways (compare figs. 3.14A and 3.14B). Check the berm level with a level.

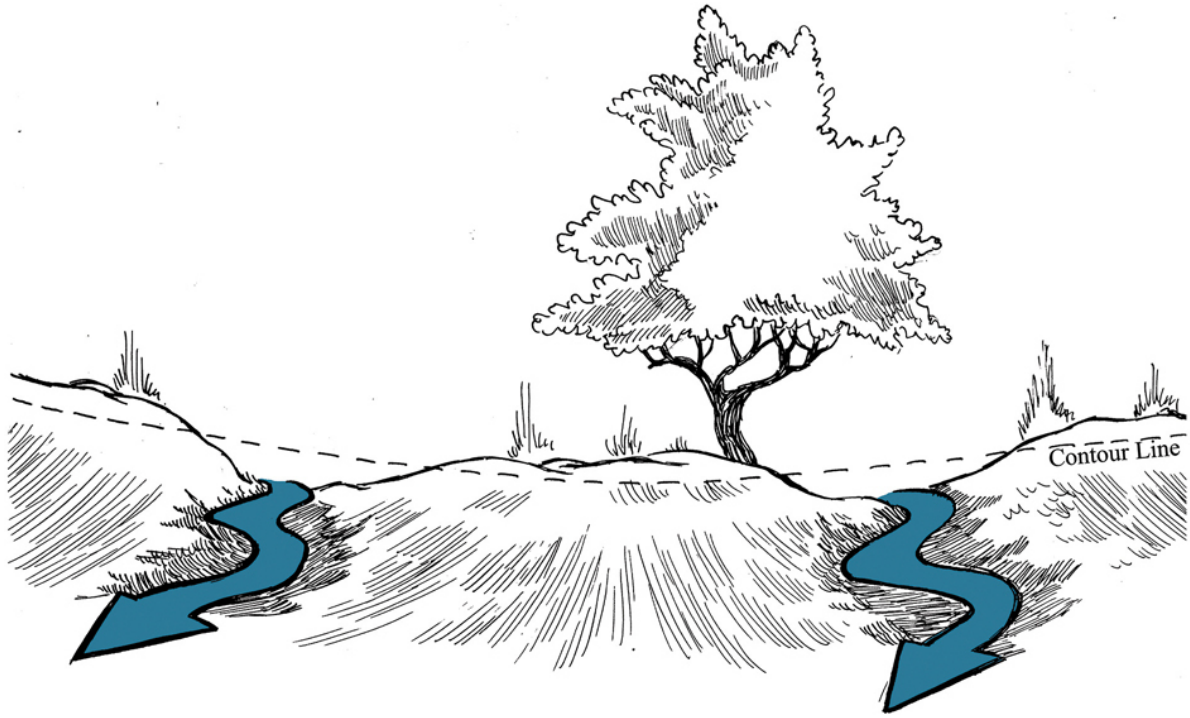


Fig. 3.14A. A failed unlevel berm with low spots that have become unplanned, unstabilized drainages (erosively cut to the bottom of the basin), which drain the berm 'n basin of all its water

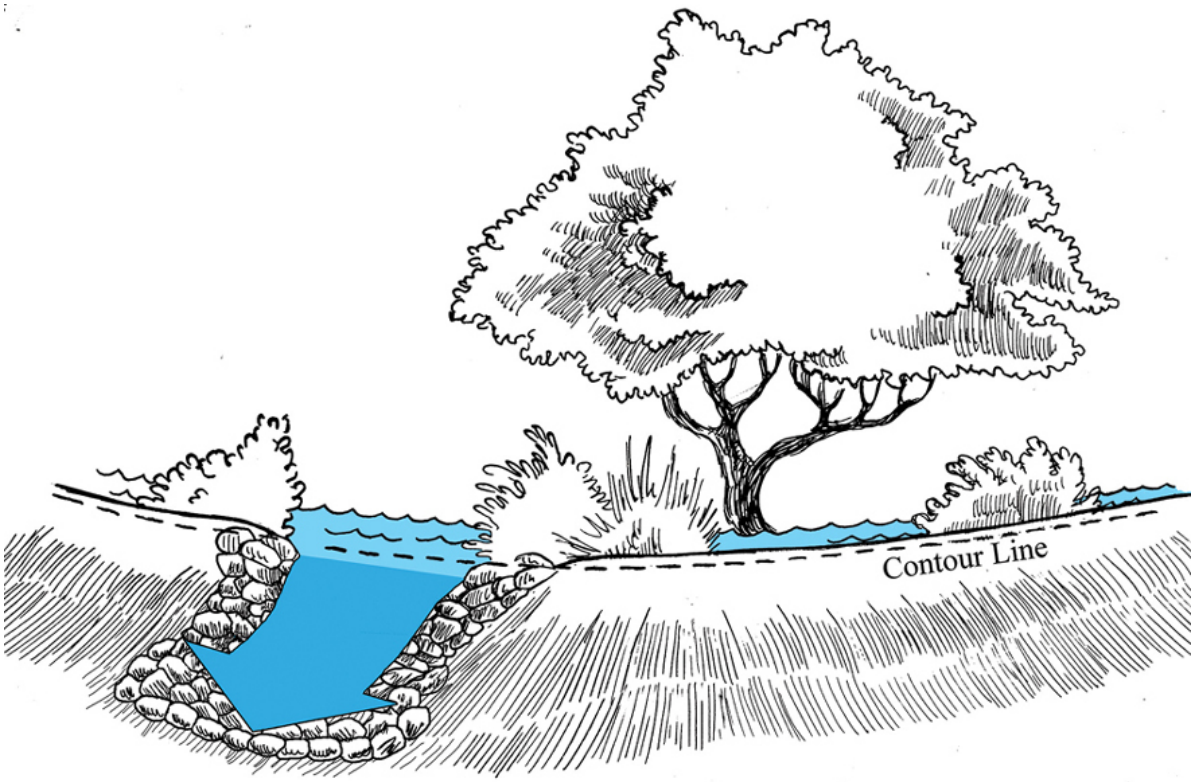


Fig. 3.14B. A successful level berm with a planned, stabilized overflow (above the bottom of the basin) allows surplus water to exit the berm 'n basin, while the majority of the water is harvested within the earthwork.

Compact your berms, but not your basins. To make berms safer and stronger, walk on them and tamp them down evenly with your feet (fig. 3.15). A mechanical tamper should be used only where the berm is a path or road, because it will compact the soil so much that very little or nothing will grow on it.

Fig. 3.15. A line of folks stomping/tamping the berm with their feet

Basins are never tamped, compacted, or sealed. Instead, they are ideally covered with mulch, and can be ripped, graveled, or loosened to increase water infiltration. Note that in wetter climates larger perennial vegetation is often planted atop the berms for better drainage. Grassed basins of diversion swales (chapter 9) are sometimes made wide enough for a tractor.

If you have ample rocks on hand, you can seed your berms with a native regevation seed mix, then lay rock only one-course or one-rock high (so seeds can germinate and plants can grow through cracks between the rock) on the top and *downslope* side of the berm for additional stabilization. Place the rocks carefully

and as close together as you can to prevent rainwater from creating concentrated rivulets between the rocks and eroding the berm (fig. 3.16).

Fig. 3.16. Boomerang berms stabilized on their downslope side with rock

LOCATION AND CONSTRUCTION OF APPROPRIATE SPILLWAY(S) FOR OVERFLOW

A spillway is a low point in the berm. Locate spillways where slopes are gradual, vegetation is well established, and soil has had little disturbance, so you can easily control and utilize the overflow. Avoid steep, disturbed, or sparsely vegetated slopes prone to erosion.

Since the downslope side of a berm creates a steeper slope than existed pre-berm, you may want to consider a less-erosion-prone, berm-less overflow spillway (see figs. 3.22, 3.23, 9.10, 9.11 and the Spreader Drain in Real-Life Examples in chapter 9).

Zig-zag, i.e., stagger, your overflow spillways. When you have a series of berm 'n basins, one above the other, offset the spillways from one b'nb to the next rather than placing one spillway directly above another. Overflow will then zig-zag

across the landscape slowly, spreading and infiltrating into the soil, instead of draining straight downhill (fig. 3.17).

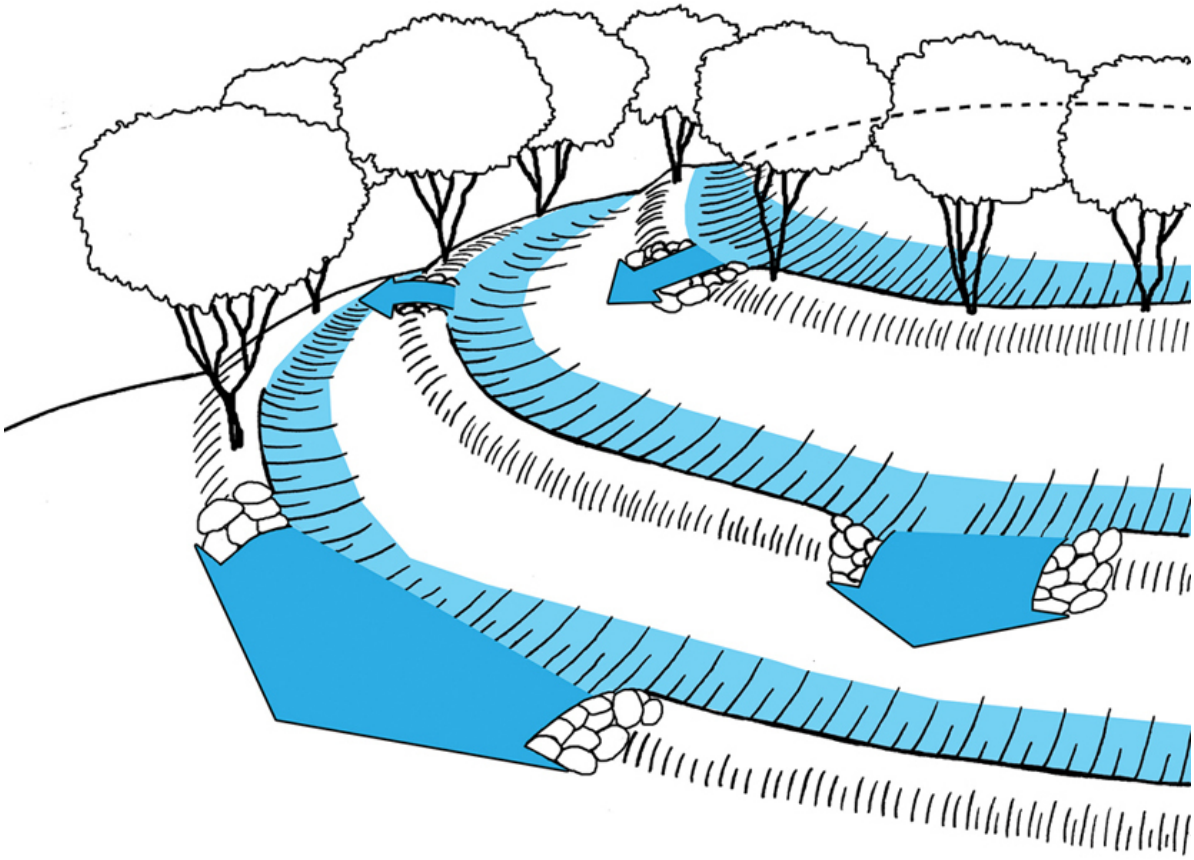


Fig. 3.17. Spillway tips:
• Zig-zag overflow spillways to spread and infiltrate more of the water's flow.
• Err on the side of wider, higher-capacity overflow spillways that spread, rather than channelize overflow.
• Widen overflow spillways, and increase their capacity, as you move down the watershed because potential total runoff volumes increase.

In principle, if you start at the top of your watershed and have enough berm 'n basins, they shouldn't completely fill with water except during particularly large storms. Such storms will eventually come. This does not mean you should over-prepare by building the Hoover Berm. Rather, incorporate a series of spillways into your berms so when they do overflow, it occurs where you've planned for it. That way the long-term effect of your work is productive not destructive—the goal of the fifth water-harvesting principle, *always plan an overflow route*.

Spillways should be indented to around 1/3 the height of the berm in your b'nb. Using this rule of thumb, a small berm that is 12 inches (30 cm) in height

would have a modest spillway indented 4 inches (10 cm) below the top of the berm. A 3-foot (90-cm) tall berm would have a spillway that was 12 inches (30 cm) below the top of the berm. This creates a safe, effective spillway while keeping as much storage capacity as possible in your b'nb.

Build your spillway wide—at least twice as wide as your berm height, measuring from the bottom of the basin to the top of the berm. The spillway will then be less likely to clog with debris, and the water flowing through it will be less constricted and erosive.

If you have a large watershed draining into your berm 'n basin you may need more than one overflow spillway to ensure that you have adequate overflow capacity to handle the incoming water. Ideally you will start implementing water-harvesting earthworks at the top of your watershed and work your way down slope, breaking the larger watershed up into a series of smaller watersheds spaced between earthworks.

Spillways should be stabilized with rock, dense vegetation, or other durable materials, so fast-flowing water won't erode the berms and land downslope. Establish vegetation such as native grass as soon as possible to anchor everything in place. Rocks can be undercut if big storms hit before plants become established. This is called piping. To prevent this, place a granular filter of unwashed mixed-sized gravel under the rocks (box 10.2).

Caution: Keep your berms from flooding what you don't want flooded

To avoid unwanted flooding, examine the area upslope of your desired berm location to see if anything is located there that will be harmed by standing water backing up in the b'nb. If so, relocate the proposed berm downslope to prevent harmful flooding.

Once you've built a berm, double check it with your level tool (appendix 1). Place one stake of the level on top of the berm's spillway. Place the other stake upslope of the b'nb at a spot level with the top of the spillway. Mark that spot—it is the highest point water can pool upslope of the berm (contrast figs. 3.18A and 3.18B). To be extra safe, use the top of the berm rather than the top of the spillway as the highest point behind which water can back up.

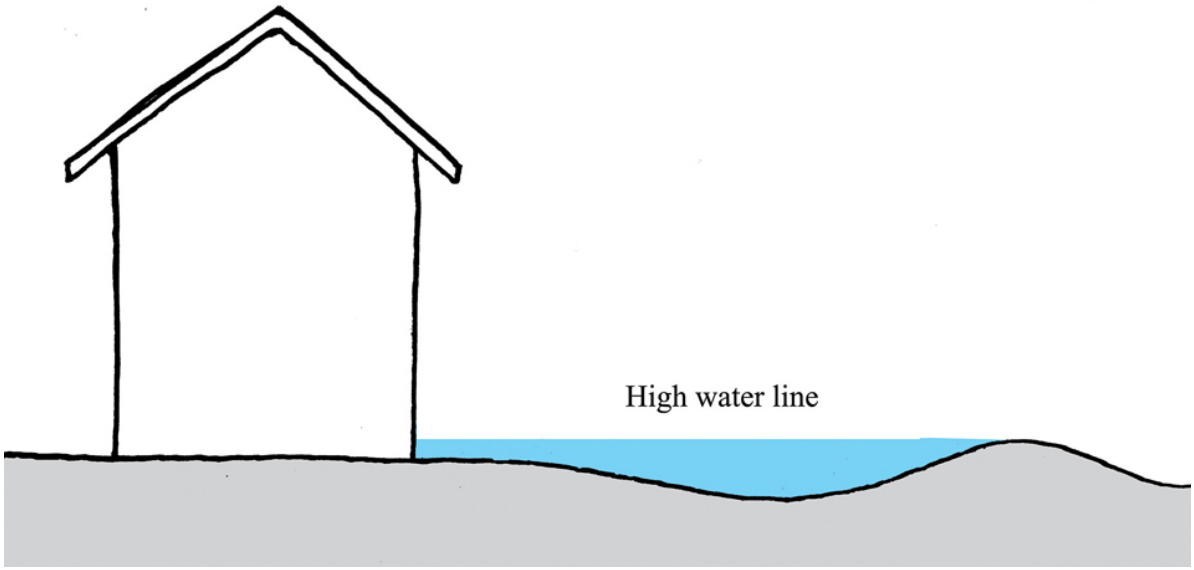


Fig. 3.18A. A poorly planned and located berm 'n basin backing water up against the house

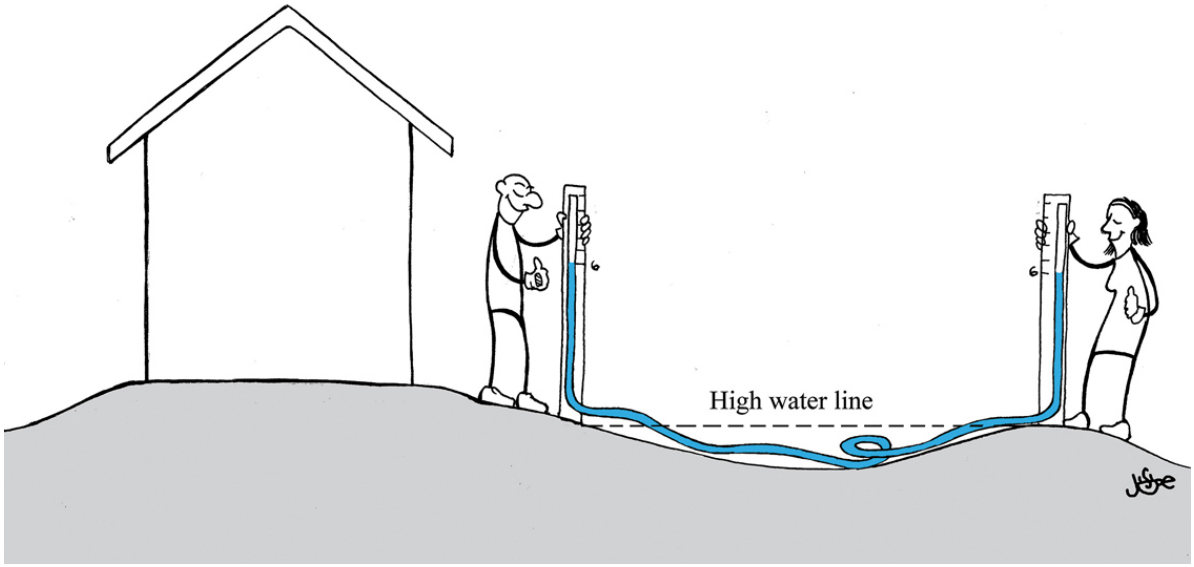


Fig. 3.18B. A well-planned berm 'n basin that won't back water up against the house

If there is still a threat of unwanted flooding, lower the height of the spillway or berm, or move the whole b'nb downslope.

PLANTING YOUR BERM 'N BASIN

Grow a maintenance team within your b'nb. Vegetation's roots aerate and stabilize the soil. Leaf drop decomposes, creating more fertile soil, encouraging

the infiltration of water and promoting life and growth. Plants store water in their roots, stems, and leaves; reduce erosion; produce oxygen; attract wildlife; and provide food and shade. Bare earthen berm 'n basins erode, but *living* b'nbs covered in vegetation grow and strengthen themselves.

I prefer to plant right in the basins where water concentrates, especially when planting desert trees that typically grow at or near drainageways, so they're tolerant of temporary flooding. Some folks in wetter climates prefer to place plants downhill of the berms, on top of the berms, or uphill of the basins so plants are outside the basins and won't be temporarily flooded during rains. See what works best for your situation. So that your earthen berm won't erode away in heavy rains, you will also want to rake in native low-water-use groundcover or grass seeds on the berm itself. Select the seed of local plants that naturally grow on exposed dry areas like your berm. Rake the seeds in a bit (to shelter them from predators and the wind), then let the rain germinate them, though supplemental irrigation can dramatically speed up the revegetation of the berm.

If you don't buy seed or nursery-grown plants, then collect seed from desirable plants found on site or nearby and scatter these seeds across your b'nbs. Gather organic matter for mulch and put that in the basin too. This will conserve moisture, improve soil, and further enhance microclimates for plants. Some seeds may like to germinate in mulch while others might be suppressed by mulch. So scatter seeds both inside and outside your b'nb to give seeds a chance to germinate in their preferred microhabitat.

For more information on how to plant, see chapter 11 on vegetation; for more specific information on mulch, see chapter 7.

MAINTENANCE

Check your berm 'n basins often, especially during and after storms. If spillways are eroding, reinforce them. If berms are blowing out, make them bigger, or see if other water-harvesting strategies can be utilized above them. If a b'nb was misplaced off contour and acts as a water drain, then build small internal berms or one-rock dams (chapter 10) within the basin area, positioned perpendicular to the main berm to intercept the water before it drains away. These internal berms or one-rock dams should be no taller than 2/3 the height of the main berm so they don't divert overflow water out of the earthwork (fig. 3.19).

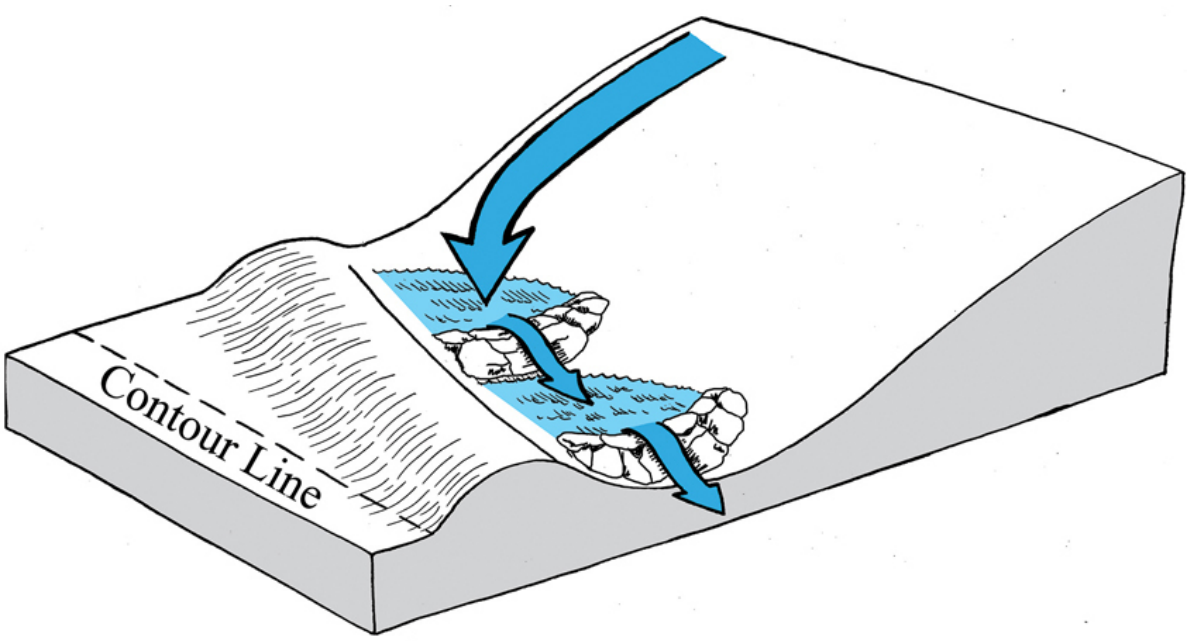


Fig. 3.19. One-rock dams placed within a berm 'n basin mistakenly placed off contour

Bare earth berms will erode, and over time they can erode to be lower than spillway overflows protected with rock, at which point new unstabilized and highly erosive overflow points will form making the berm useless. So stabilize your berms with vegetation, rock, or other means and ensure through maintenance they remain significantly higher than their spillways.

Basins will also fill over time with sediment carried by incoming runoff. So, strive to increase stabilizing vegetative cover of the berm 'n basins catchment areas, while moving captured sediment to the berms as needed.

VARIATIONS OF BERM 'N BASINS

CONTOUR BERM 'N BASIN

A *contour berm 'n basin* is constructed along a contour line, which is a level line perpendicular to the slope of the land. This strategy can retain runoff water across an entire slope. The length of a contour b'nb is up to you and the site; it could be from 2 feet to 2 miles long (fig. 3.20). Curve both ends of your berm uphill and taper the ends into the slope. This way when it rains, water will be retained by the contour b'nb and will infiltrate into the soil, rather than running erosively out the ends of the b'nb (see fig. 3.21; see box 3.4 for an example). In areas with a lot of rock, stone berms can be built with or without soil.

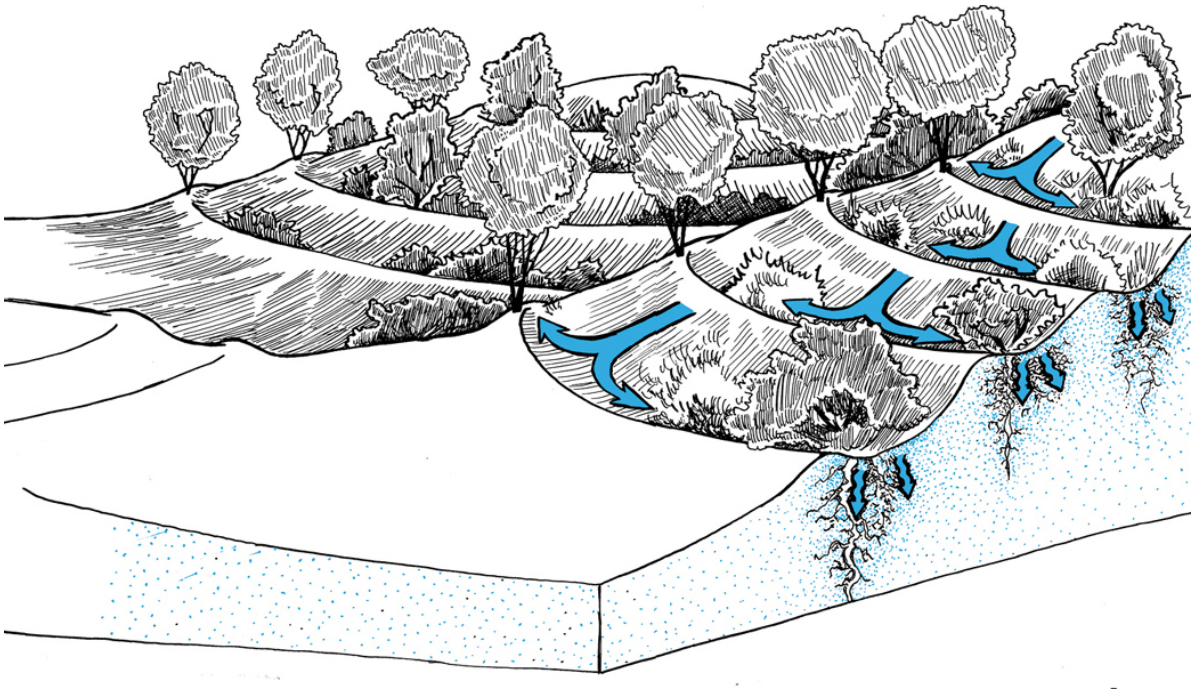


Fig. 3.20. Contour berms Note: aim to fully vegetate b'nbs. Plants were removed here so you can see the earthworks.

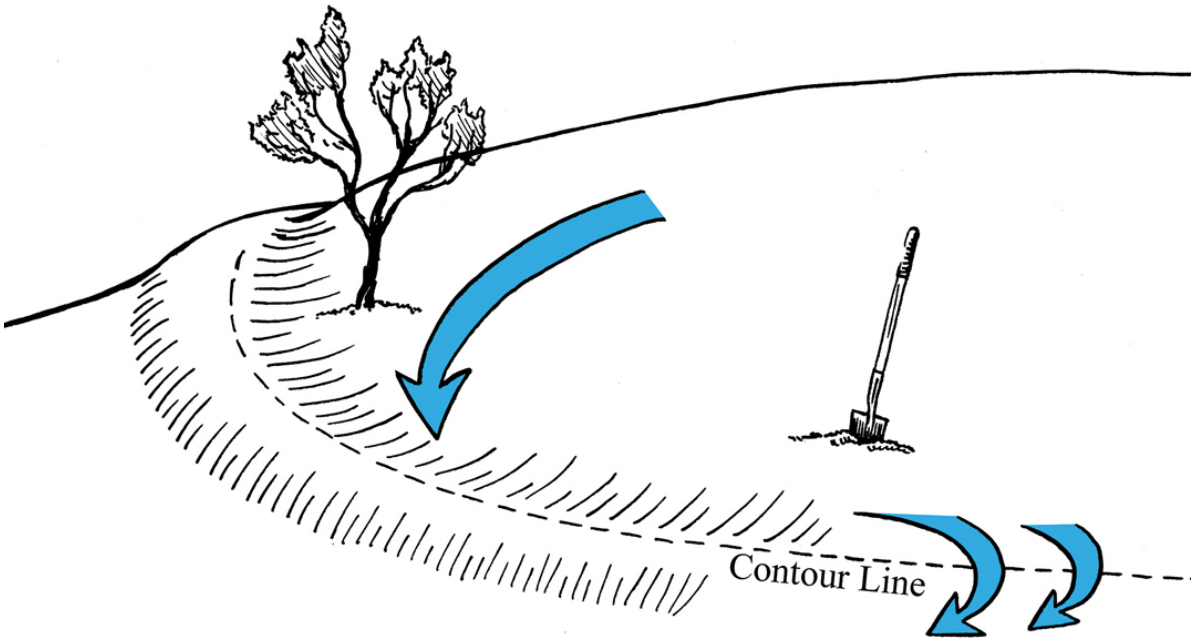


Fig. 3.21A. An unfinished contour berm draining water out its incomplete end

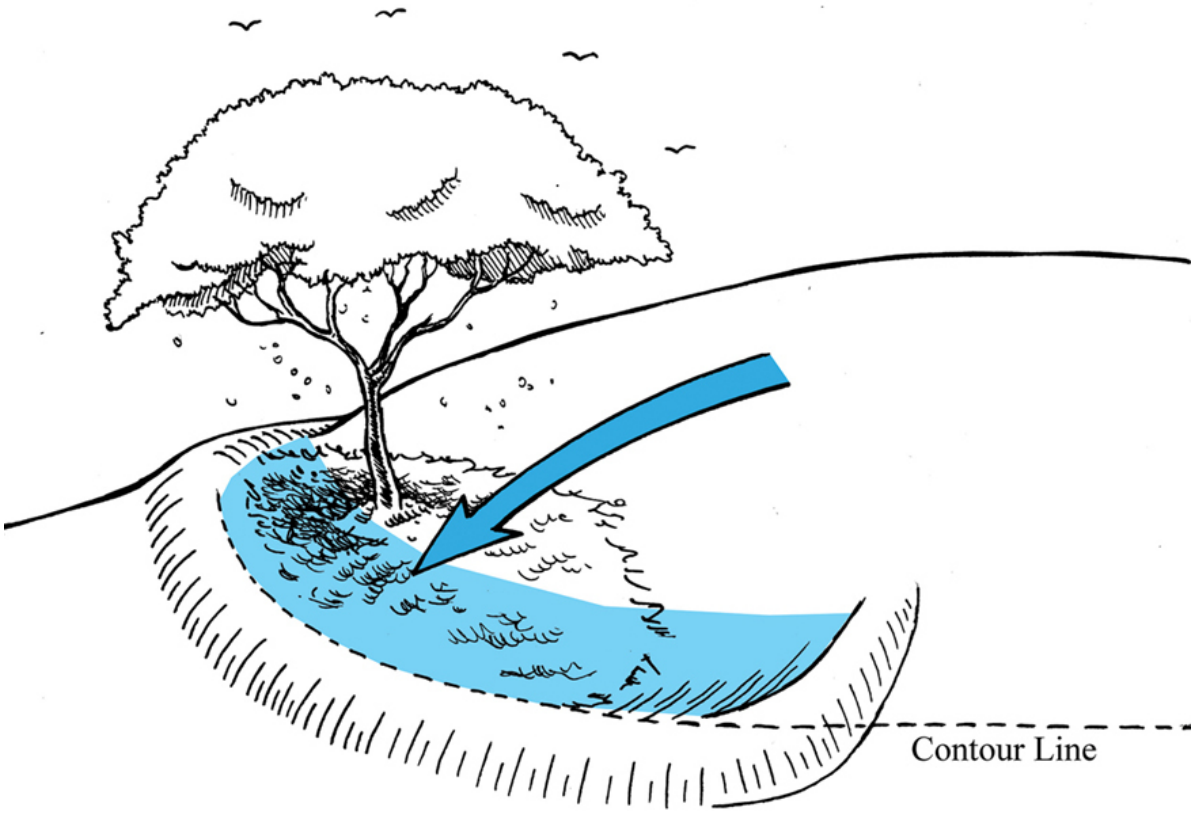


Fig. 3.21B. A finished berm harvesting water, organic matter, and soil

Box 3.4. A Water-Harvesting Plant Nursery Laid Out in Contour Berms

For years, friend and permaculturalist Chris Meuli has harvested water successfully in the soil to grow hundreds of trees he plants after growing them out in pots (see his Real Life story in chapter 7 on mulch). Now, he uses these trees, while they are still growing in their nursery pots, to harvest even more rainwater. The pots are set along the contour of his sloping land in rows three pots deep, creating "nursery-pot contour berms" nestled in a mature stand of sheltering pinyon and juniper trees. Chris covers the sides and tops of the pots with mulch to reduce soil temperature and evaporation loss. This strategy reduces Chris' irrigation needs and acts as a form of erosion control. A hose connected to a rainwater cistern upslope of the nursery provides irrigation water. When irrigation water drains through a pot, the excess water is now caught or slowed by the berm made of pots and mulch, so more infiltrates into the soil and waters the surrounding pinyon and juniper trees. And when it rains the contour pots catch stormwater.

Build contour berms only in more gradually sloping depositional areas where more sediment is gained by deposition than lost to erosion (fig. 9.5).

BOOMERANG, FISHSCALE, AND SMILING BERMS

Boomerang, *fishscale*, *half moon* or *demi lune*, and *smiling berms* are different names for the same type of b'nb (see box 3.5 for an example). From here on, we'll call them boomerangs. They are semicircular in shape with the curved ends facing upslope, like someone opening their arms to the upslope water as if to give it a big welcoming hug: "'Cause we love that water!" Boomerangs concentrate water around an existing or proposed plant. You can create just one or a whole array of them. A hillside of native trees or a fruit orchard planted in boomerangs resembles "miles of smiles."

Box 3.5. Boomerang Berms Revegetate Degraded Land

At the Tucson Audubon Society's Santa Cruz River Habitat Site northwest of Tucson, boomerang berms are helping revegetate sloping sandy flood-control dikes, while reducing the need for irrigation. Project manager Ann Audrey reports that, "In a test-plot area, native vegetation was planted with and without boomerang berms to compare the results. After the first significant summer rain of the season, the soil moisture only reached a depth of 4 inches (10 cm) where no boomerang berm existed. Yet, where there were boomerang berms, soil moisture reached a depth of over 20 inches (50 cm). A year later, plantings within berms are noticeably bigger and healthier than those without such earthworks."[2]

The two ends of a boomerang berm are typically level with one another, while the rest of the berm dips downslope to create a cuplike shape. However, the top of the berm is raised in the middle, so the height of the berm will be shorter at the ends of the berm and taller in the middle of the berm. Mark the two level ends of the boomerang with a water level or A-frame level, then mark the location of the rest of the berm from end to end. That done, dig out the basin and make the berm. Or, just make the berm by bringing in soil.

Stabilized spillways can be situated at one or both of the curved ends of a boomerang (figs. 3.22 and 3.23). To direct overflow around just one end, make that end a little lower (further downslope) than the other. Use an A-frame or bunyip water level to check your work. When creating a series of boomerangs always direct overflow from one to the next to attain the spread and sink principle.

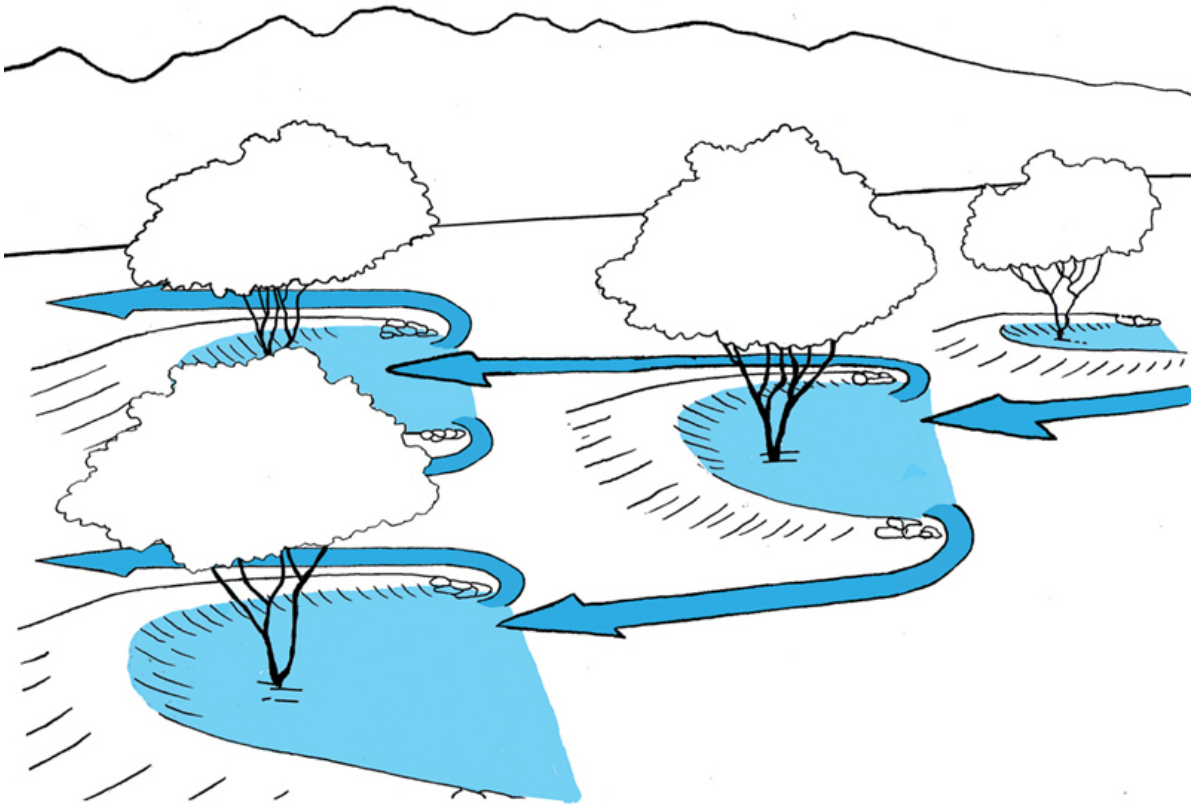


Fig. 3.22A. A series of boomerang berms overflowing one into the other. Select/plant/place vegetation based on its water needs and tolerance. Water-tolerant/water-needy trees illustrated here.

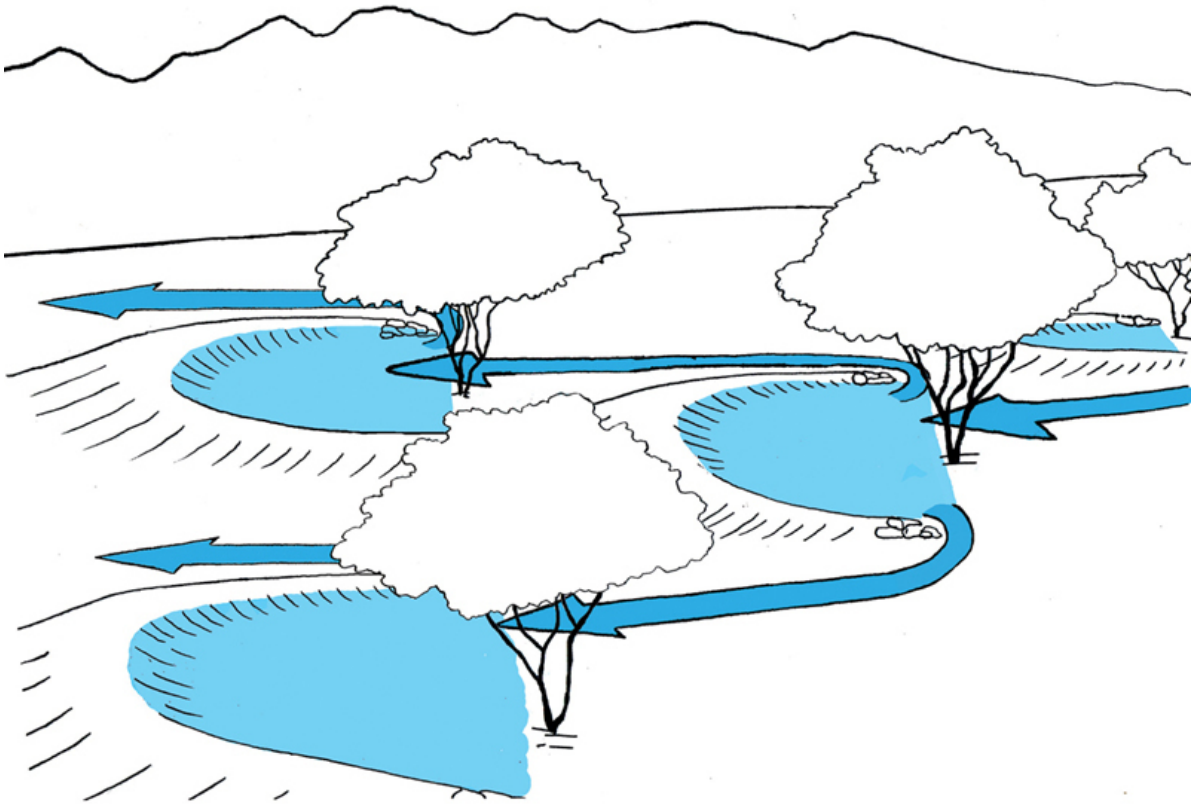


Fig. 3.22B. Less water-tolerant trees

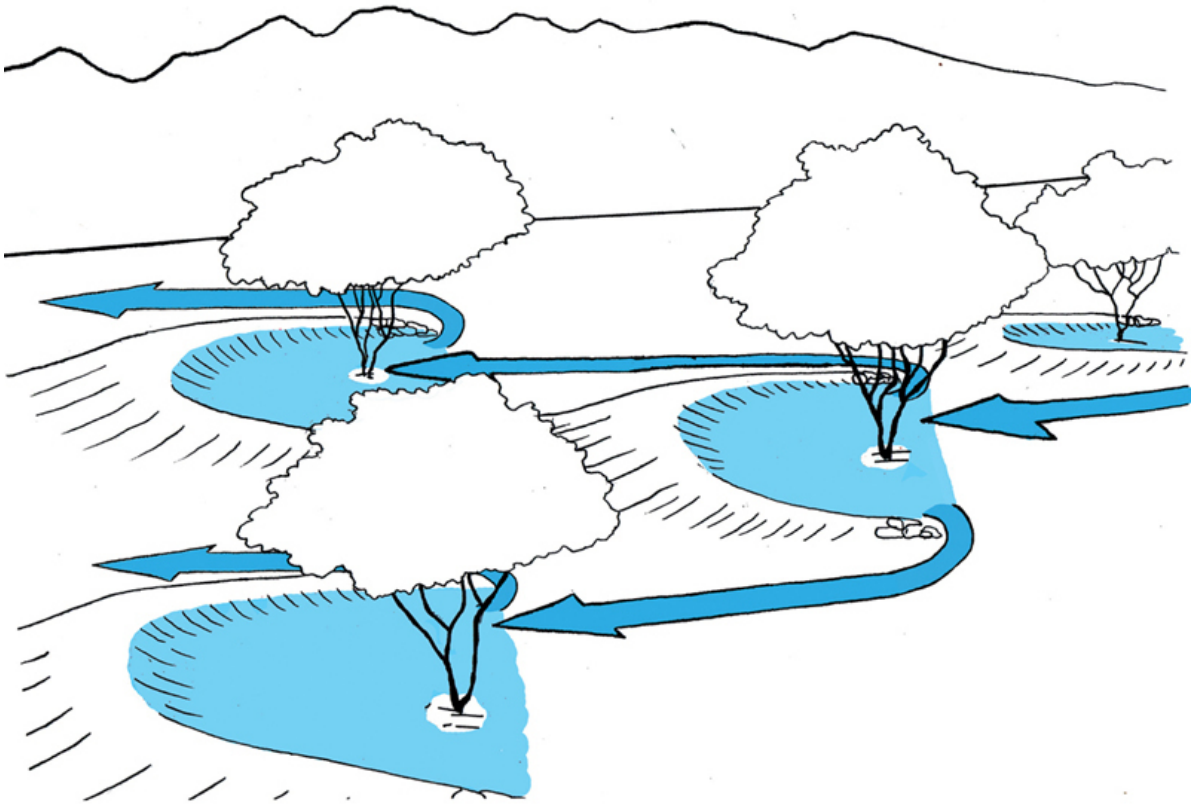


Fig. 3.22C. Planting on raised pedestals avoids too much water against trunk

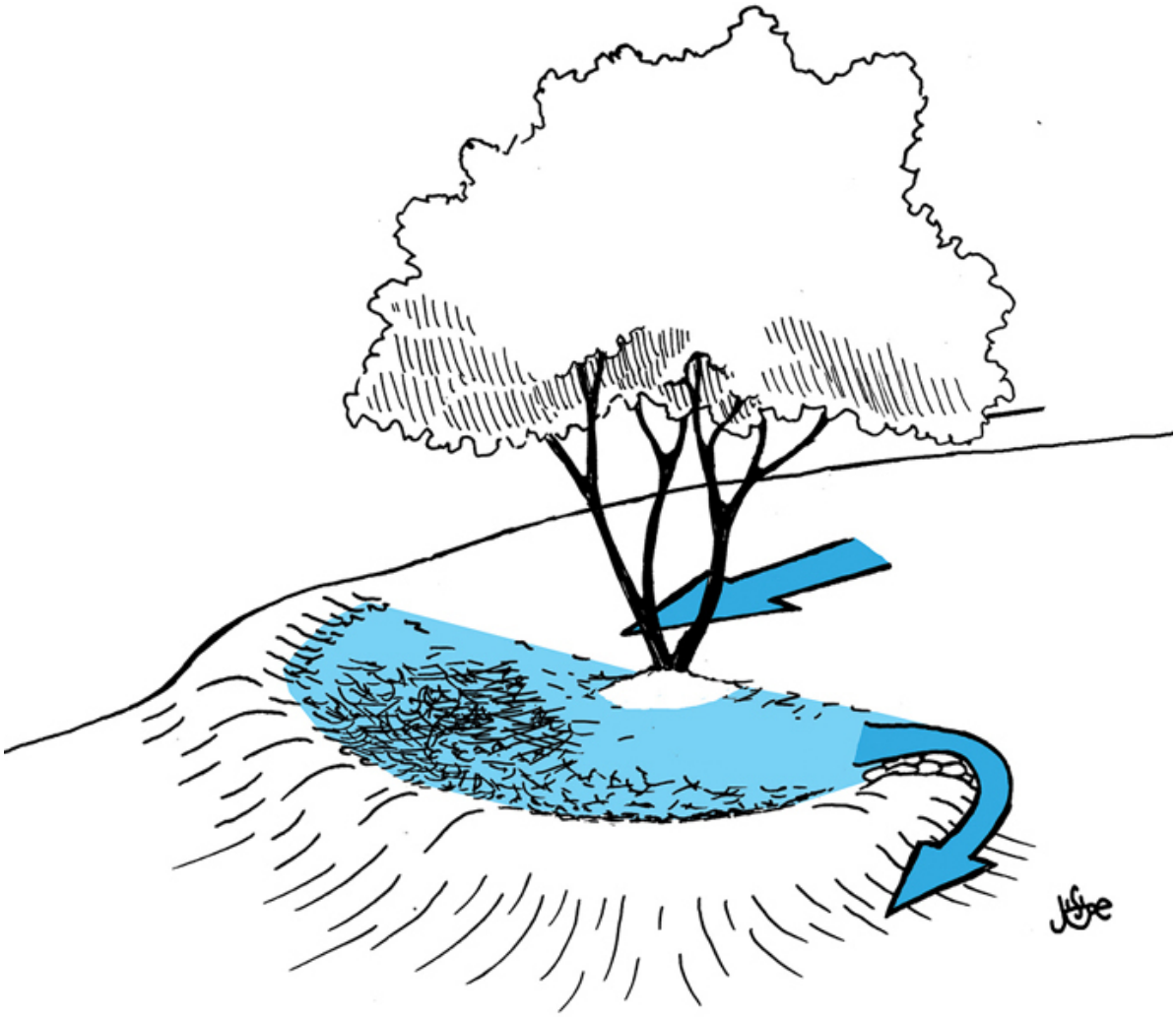


Fig. 3.23. A boomerang berm with one end stabilized with rock and made slightly lower than the other end to act as an overflow spillway

I love that boomerang spillways don't increase steepness and speed of flow, since they spill to the existing grade/slope of the landscape—not over a steeper berm.

NET-AND-PAN SYSTEM

A net-and-pan system is a modified series of boomerang berms connected directly to one another, concentrating harvested runoff at multiple points in the landscape. A completed system looks like a "net" of berms draped over a hillside with "pans" or basins inside each segment of the "net" (fig. 3.24 and 3.25). The height of a berm in a net-and-pan system is consistent from one part of the berm to another. See box 3.6 for an example.

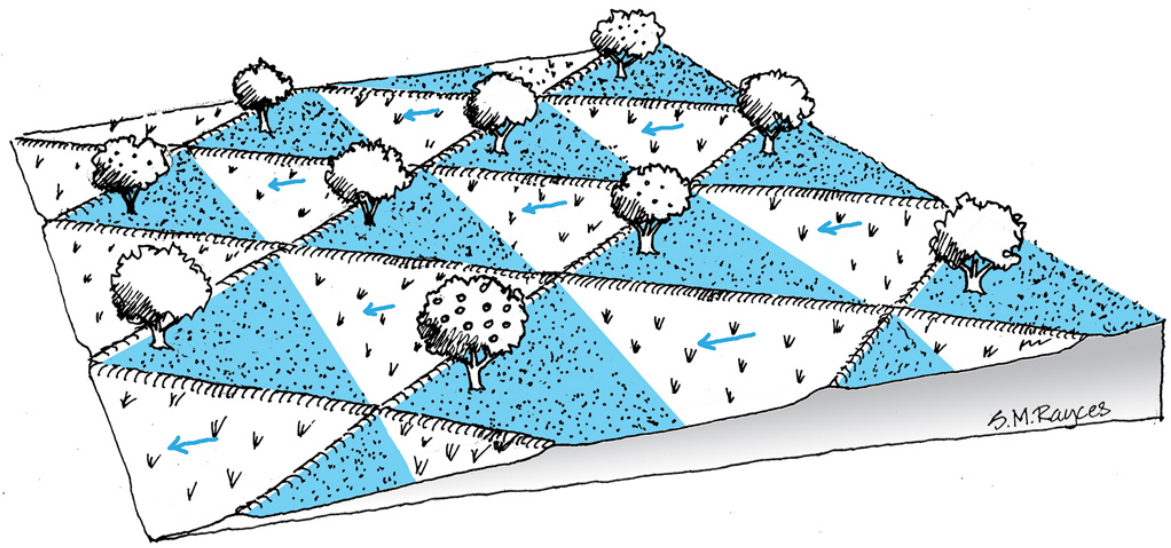


Fig. 3.24. A net-and-pan system of berms. The upper half of the pan is a catchment surface draining water to the lower half where the water infiltrates into the root zone of the tree.

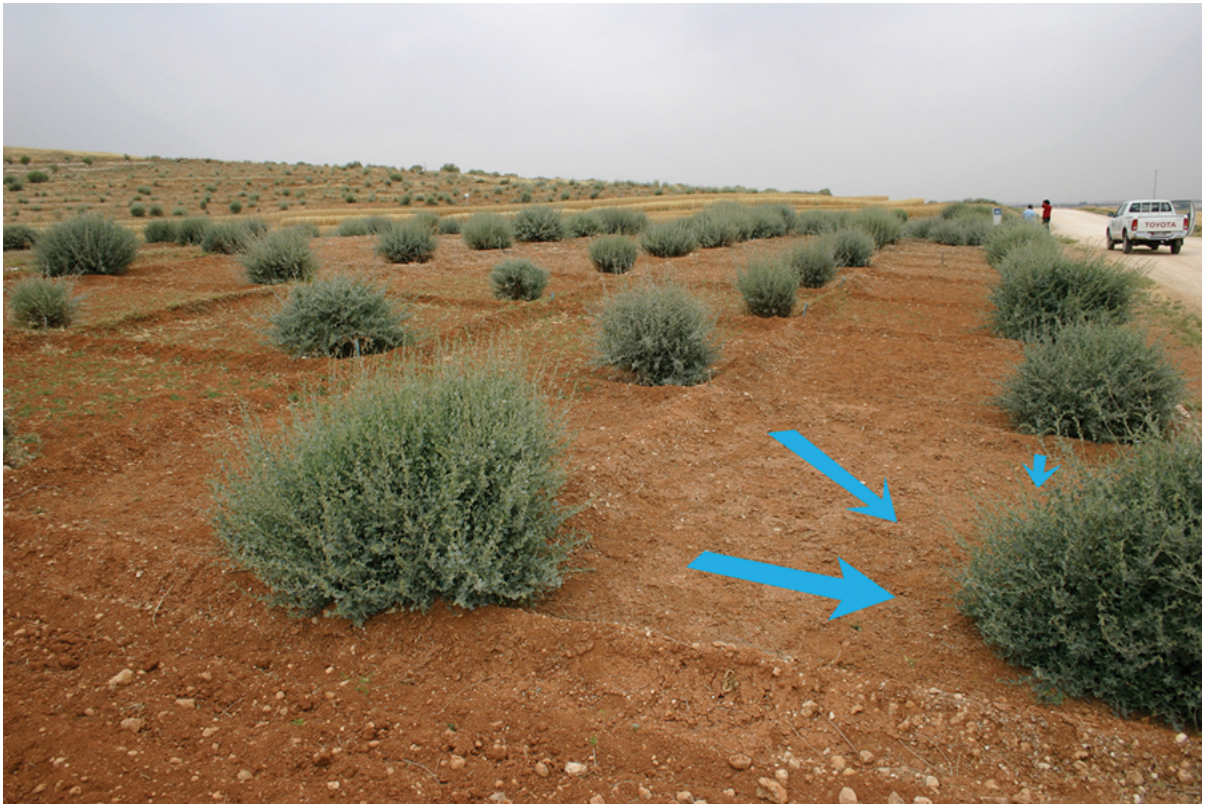


Fig. 3.25. Net-and-pan berms at ICARDA research farm outside Aleppo, Syria. Saltbush (*Atriplex*) at the low point, grown for livestock fodder, is watered solely by captured rainfall. Erosion may occur on slopes steeper than 5%, which would necessitate larger berms.

Box 3.6. A Net-and-Pan Orchard System in the Negev Desert

In the Negev desert of Israel, botanist Michael Evenari successfully grew an orchard of olives, apricots, pomegranates, almonds, grapes, and saltbush for pasture on a scant 4.1 inches (105 mm) of average annual rainfall without supplemental water.

He planted each tree, vine, or shrub within its own microcatchment—a separate microwatershed ranging in size from 168 ft^2 (15.6 m^2) to 10,760 ft^2 (1,000 m^2). Each microcatchment or "pan" in Evenari's orchard was surrounded by an earthen berm or "net" about 8 inches (200 mm) high. These berms captured the rainfall and concentrated its moisture within the broad root zone of the planted tree or vine. Microcatchment size was based on the water needs of the plants and the amount of rainwater expected to fall within the earthwork (appendix 2 gives you the calculations to do the same; appendix 4 in Volume 1 provides water needs and calculations for plants).

The greater a plant's water needs, the greater the size of its microcatchment—up to a point. Evenari found that if a microcatchment was too big it actually provided less benefit to the plant than a smaller microcatchment, because a significant amount of water was lost to evaporation, and much of the moisture that did infiltrate into the soil did so beyond the plants' root systems.

When sized correctly, no supplemental irrigation was needed within the net-and-pan orchard. The rainwater was simply used where it was harvested.[3]

CONTOUR PLANTINGS

Vegetation can be planted on contour to create a living berm (no earthen berm) that can grow and spread itself as its seed germinates in the increasingly moist soil around the original planting.

Such was the case with the native sheep fescue and Arizona fescue grasses Jeremiah Kidd seeded directly above subsurface irrigation lines laid on contour across the relatively barren slopes around his home. The grass has grown to create living combs of vegetation that are sometimes covered by sediment carried by the stormwater runoff. But the grasses readily grow back up through that sediment as they help slow, spread out, and infiltrate runoff when it rains. Thus the grass combs are growing and filling in the space between the original contour plantings resulting in still more harvested water and sediment (fig. 3.26).

Fig. 3.26. Native grasses grown on contour above a 4-inch (10-cm) deep drip-irrigation line create a contour "berm" of grass in Santa Fe, New Mexico. The subsurface irrigation water is treated effluent pumped from the household's septic tank, which has been augmented with a SludgeHammer aerobic bacterial generator system for enhanced treatment.

ICARDA researchers created a dryfarmed (irrigated only with rainfall) annual crop variation on their research farm, which I visited outside Aleppo, Syria (average annual rainfall of 12.9 inches or 329 mm). Contour strips, or runoff strips, are plowed across a gently sloping field, then planted with wheat, barley, lentils, and/or garbanzo beans. Available rainfall was nearly tripled by leaving bare, compacted contour *strips* (twice the width of the planted areas) above the planted areas. Rainfall runs off these unplanted strips into the planted strips just below. Planted strips do not exceed 6 feet (2 meters) in width to ensure more even distribution of the runoff within the cropped strip (fig. 3.27). And once the crop has been harvested, the catchment can be used for grazing.

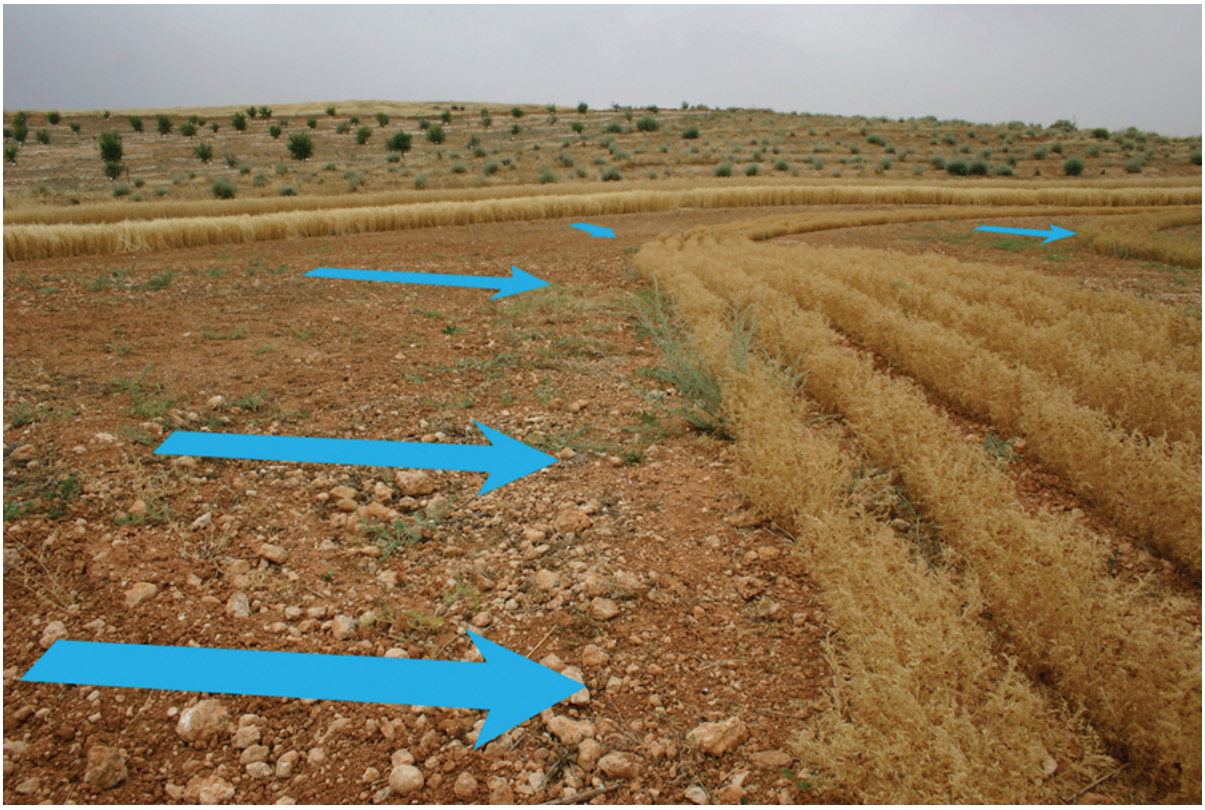


Fig. 3.27. Contour plantings of cereal crops and legumes irrigated solely by rainfall at ICARDA research farm outside Aleppo, Syria. Available rainfall is nearly tripled by harvesting runoff from bare contour strips above the planted areas. Dryfarmed olive trees planted within boomerang berms are on the left side of the hill above the field.

See fig. 3.28 for contour plantings of veggies in a wet climate/season, and the last Real Life Exmple at the end of this chapter for an example in Zimbabwe.

Fig. 3.28. Contour planting veggies in a wet climate/season. Plants on the high ridges, water in the low furrows. Commonweal Garden at the Regenerative

Design Institute, Bolinas, California. Photo: Penny Livingston

Appendix 4 lists further resources on various kinds of berms.

MULTIPLE FUNCTIONS OF BERM 'N BASINS

BERM 'N BASINS AS FIREBREAKS

Vegetation planted around water-harvesting earthworks has more available moisture than vegetation in the general landscape, so it can be more resistant to drought and fire. To enhance this effect, plant drought-hardy, fire-resistant vegetation such as salt-bush (*Atriplex* spp.), thornless nopal cactus (*Opuntia ficus-indica*), or aloe (*Aloe* spp.) within contour berms, and situate them on fire-prone slopes or in the path of prevailing winds that could carry a fire.

BERMS AS PATHS, DRIVEWAYS, AND ROADS

The berms of b'nbs can often double as raised accessways. This keeps the paths high and dry, and the adjacent basins and plant roots sunken and moist (fig. 3.29). See chapter 8 on permeable paving as well as appendix 4 for road construction guide resources.

Fig. 3.29. A berm as a raised path

BERM 'N BASINS AS EROSION CONTROL: BRUSH BERMS

Since berm 'n basins slow the overland flow of runoff, they simultaneously reduce soil erosion. Brush berms can be used high in the watershed where sheet flow of runoff is light. Lay enough brush in direct contact with the soil so you don't have big openings that would let concentrated water quickly escape and cause more erosion. You can anchor the brush in place with downslope stakes, the mass of large branches, or by partly buried branches. See brush *sheet flow spreader* strategy in chapter 10.

REAL-LIFE EXAMPLES OF BERM 'N BASINS

THE GRANDMOTHER APPROACH— DRAGOON, ARIZONA

Two senior homesteaders in rural southeast Arizona stroll their rolling land every day. As they walk, they reposition small, fallen branches or agave stalks so they lie perpendicular to the slope. They roll small rocks with their feet to create terrace-like berms, and pile prunings and brush into serpentine contour lines. They do just a little bit each day, in a relaxed, meditative way. Though slow, it *is* making a difference. New plant growth has germinated in the water-and-soil net of their simple earthworks, and this in turn is attracting ever more beneficial wildlife.

USING TREES KILLED BY FIRE TO BRING BACK THE FOREST —LAMA, NEW MEXICO

In 1996, a 7,000-acre (2,828 ha) forest fire ravaged most of Lama Mountain north of Taos, New Mexico. The Lama Foundation, a spiritual community nestled on the mountain, found itself surrounded by a scorched landscape spotted with a standing forest of dead and charred ponderosa pines. The dead trees were weak and some snapped and fell in the wind. With the land burned bare, erosion promised to be severe with coming rains.

The Lama residents decided to act. They cut the weakest trees so they would land perpendicular to the slopes, a common forestry practice called *log erosion barriers*.

The logs didn't have adequate contact with the ground so the community lopped their branches and piled them on the upslope side of the logs, then

covered everything with loose straw, creating a sturdy barrier to trap sediment. Vast networks of these log-and-branch berms were created across the land. In addition, the community built check dams of logs, branches, straw bales, and rock within the drainages (fig. 3.30).

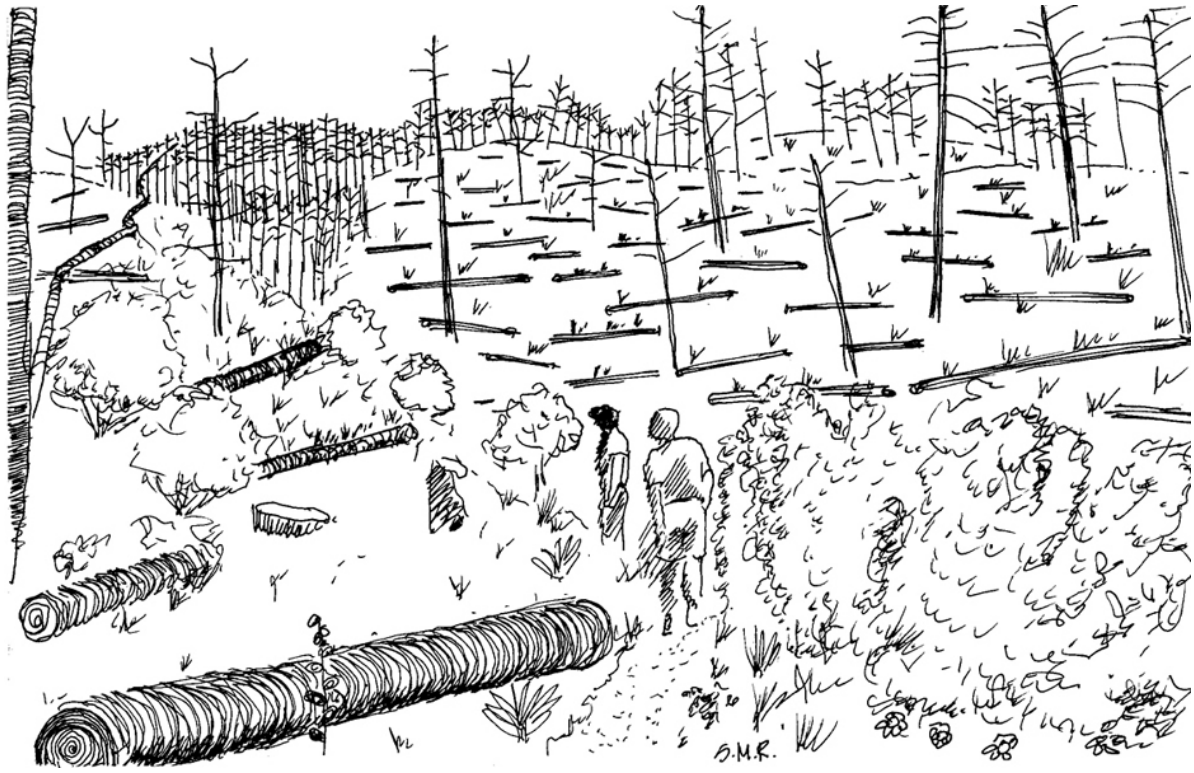


Fig. 3.30. Sketch of burned trees felled on contour to act as log erosion barriers that stabilize the landscape at Lama, New Mexico

While the community had done extensive work, it wasn't enough to prevent a devastating flow when the first big storm hit. The lack of material and vegetation to absorb rainfall and brake runoff, in combination with the high mobility of loose ash and fire-scorched soil, led to sediment and stormwater pouring down the slopes.

However, the check dams and most of the log-and-branch berms held firm. These structures trapped soils, sediments, and seeds, creating a foothold where revegetation could begin. Millions of small plants volunteer plants popped up around the berms, creating "living berms" of new vegetation. With the help of these plants and the earthworks constructed by the community, the land recovered faster here than other areas affected by the fire.[4]

HARVESTING WINDSWEPT SNOW WITH WINDBERMS—MORIARTY, NEW MEXICO

By Chris Meuli

During the severe drought of spring 1996, the Lama Foundation wildfire north of Taos, New Mexico, made me look at my semirural land through new eyes. Convinced that such a disaster could also happen in Edgewood, I thinned pinyon pine and juniper trees that were crowded, diseased, or too close to buildings. (Later, I was surprised how many micro-climates this tree thinning would create. Around the remaining trees, a circle of shade shifted daily where there had previously been a deep darkness under the crowded crowns of the trees. These circles of sunshade interface created a great diversity of sites suitable for a variety of planting.) Then the question was, "Where can I use this biomass that I've thinned with the least amount of work for the greatest benefit?"

Nearby, on the windswept, treeless high plains desert near Moriarty, New Mexico, I have been working for over a decade to establish windbreaks. But the versatile honey locusts I planted in the 1980s had stopped growing vertically and started growing horizontally in the persistent wind of this site. More recent plantings of hardier evergreens paired with contour berms were faring better, but to improve success, the drying effect of the harsh wind needed to be addressed. So I hauled the thinnings ("slash") from Edgewood over to Moriarty to construct windberms for the young windbreak trees. Windberms are built structures that serve the same purpose as traditional windbreaks, which are typically "grown." The idea was to slow the wind down, deflect it off the ground, and attenuate its strong mechanical forces. Perhaps the windberms would also harvest moisture during the blowing winter snows.

At this 20-acre (8-ha) site a relentless westerly wind blows virtually parallel to the contour, and annual precipitation averages 14.5 inches or 368 mm at an elevation of 6,217 feet or 1,894 m. During most days, the wind is a constant 5 to 15 miles (8–24 km) per hour with regular gusts to 15 to 45 miles (24–72 km) per hour in the spring. By feeling, hearing, and seeing the patterns of blowing sand and debris, I knew that the wind direction varied 30–45 degrees from moment to moment. Windberms curved with their "backs" into the wind, so to speak, could address this constant variation.

Based on traditional windbreak design, windberms should be semipermeable so that they can filter and slow the wind. In contrast, a solid wall of material can cause scouring and actually amplify wind effects. A windbreak will calm the wind to a distance 3 to 5 times the height of the windbreak on the windward side and to a distance 10 to 15 times the height of the windbreak on the leeward side. Berms can be placed to complement or alter the existing patterns created by water flows, roads, fences, structures, windbreaks, and human and animal paths.

Tree slash, cactus cuttings, prunings, discarded lumber scraps, and many other "waste" products prove useful in constructing a windberm. Established trees, shrubs, and cacti can anchor the berm to the ground.

Fifteen pick-up loads of slash were sufficient to construct five windberms, each 3–4 feet (0.9–1.2 m) high and 40–120 feet (12–36 m) long. Stacked in interlocking patterns, the slash did not blow apart in gusts of wind. Overlapping the ends of the windberms prevented wind from funneling between two adjacent windberms while allowing room for walking and pulling a cart between them (fig. 3.31).

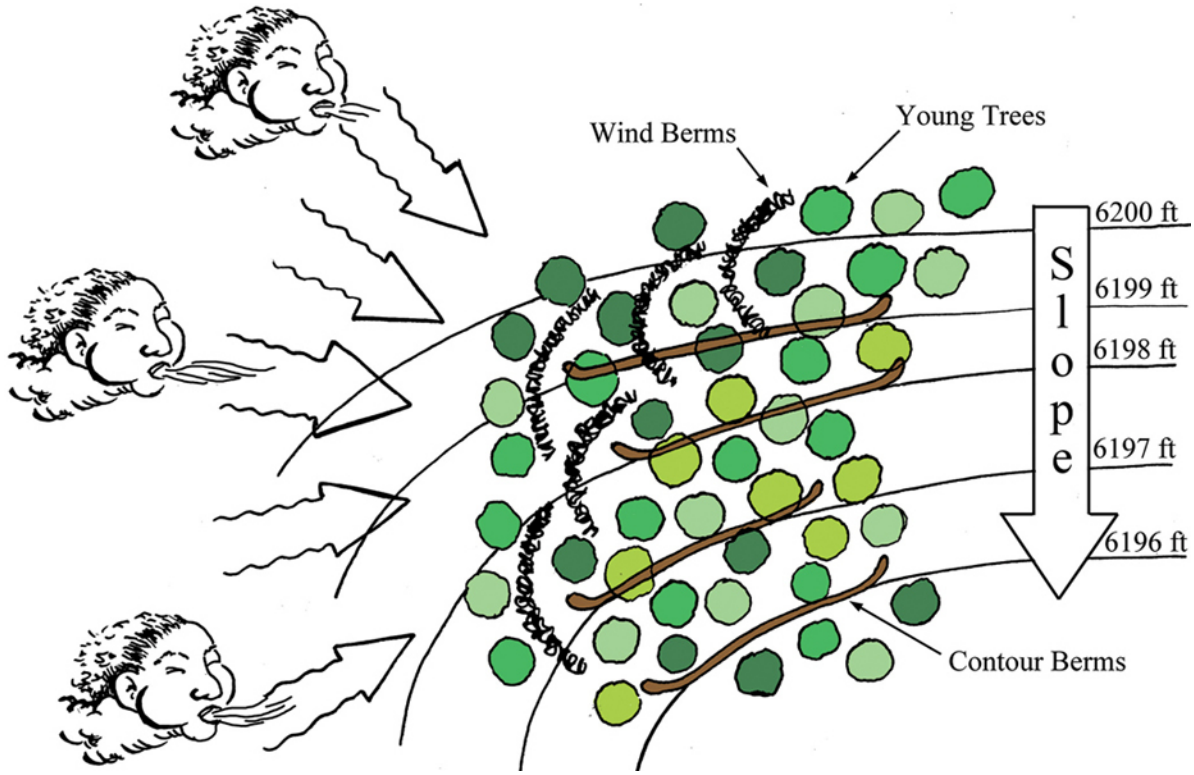


Fig. 3.31. Plan view of Chris Meuli's windberms, contour berms, and young tree plantings

By the end of the summer, the slash had dropped most of its needles, mulching the ground beneath it and adding much-needed organic matter to this recovering former cattle range. The berms also enhanced the habitat for reptiles and small mammals.

The effect that the windberms had on a snowfall the following January was dramatic. Severe winds blew the 16 inches (40 cm) of snow off of my neighbors' land into drifts that were 2 to 3 feet (0.6–0.9 m) deep on both the windward and lee sides of the windberms (fig. 3.32).

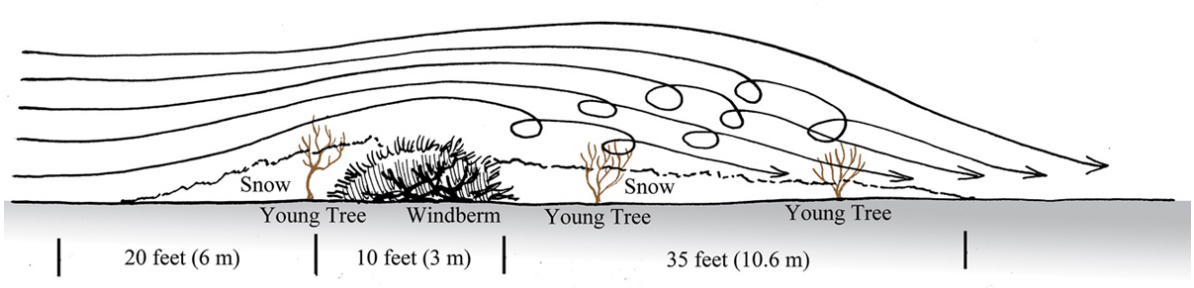


Fig. 3.32. Side view of windberms, young trees, and harvested snow

Two years later, there is a dramatic increase in the size and health of the trees on both sides of the wind-berms compared to trees further away. A great diversity of vigorous groundcover and grass has grown up in and alongside the berms. These enhance the wind-modifying, shading, mulching, and water-retention effects.

Chris Meuli experiments with simple techniques that enable humans to live sustainably in New Mexico. You can contact him by email at mpermadr@msn.com.

This story is adapted from an article that first appeared in the Permaculture Drylands Journal*, Number 31, Winter, 1998. Used with permission.*

See the "Wind & Snow Harvesting" page at HarvestingRainwater.com for more on wind and snow harvesting, diversion, and deflection strategies.

BERM 'N BASINS IN WET LANDS— OREGON

Toby Hemenway, author of the wonderfully integrated gardening guide *Gaia's Garden*, is an avid fan of berm 'n basins, which he calls "swales." When he lived in southern Oregon, rain fell all winter, but could cease for months at a time in summer. On the slope just below his home, Toby dug an 80-foot (24-m) long, 3-foot (0.9-m) wide berm 'n basin. As Toby states (in which he refers to b'nbs as swales), "It's made a tremendous difference, holding moisture long after the rains have gone. Come summer, above the swale the grass shrivels and browns within

days after the rains stop. Below it, not only does the greenery remain verdant for weeks longer, but many new wildflower species have spontaneously appeared in the welcoming microclimate. Humus is building, diversity is growing. I've found that letting water concentrate and soak in via swales will store it in the soil deeper and longer than if the water simply spreads across level ground. I'm sold on swales."[5]

WOOD CHIP BERM 'N BASINS

See Real-Life Examples at end of chapter 7.

CONTOUR BERMS AND PLANTINGS INCREASE YIELDS AND RAISE FISH IN ZIMBABWE

In dry Mazvihwa, Zimbabwe (average annual rainfall 17 inches (450 mm), innovative farmer Bouwas Mawara has planted the rain to great effect (fig. 3.33). In 1980, after Rhodesia became Zimbabwe, Mr. Mawara transformed a series of 1:200-sloped water-draining diversion drains on his farm (which had been required by the Rhodesian government) into water-harvesting contour berm 'n basins about 3 to 10 feet (1 to 3 meters) deep and 6.5 feet (2 meters) wide.[6]

Fig. 3.33. Bouwas Mawara on right and Abraham Mawere Ndhlovu of the Muonde Trust on left in a field of Mr. Mawara's contour plantings bordered at top and bottom by contour berm 'n basins planted with fruit trees and perennial grasses.

The berm 'n basins were then planted with fruit trees and perennial grasses for livestock fodder, erosion control, and roof thatching. Now, between the berm 'n basins, he plants his annual crops on contour; and he has diversified his plantings to include many hardy heirloom crops such as finger millet, which is much more drought tolerant than other grains grown in the area.

He catches fertilizer in the form of harvested nutirent-rich rain, runoff, and the organic matter it carries; and grows fertilizer in the form of nitrogen-fixing legumes, manure from his livestock and wildlife, compost, and the life in his organically-farmed soils. He feeds his soil not the crop, or as he says, "I feed the pregnant mother to feed the child."

As a result of these efforts, he is able to dry farm winter crops every dry season, including dry years when non-water harvesters get no crop s. He raises fish in

water caught in his contour berm ‘n basins (where bedrock and clay help hold the water), and even had excess water in the severe droughts of 1992 and 2008.[7]

To share such innovations and benefits among area farmers Mr. Mawara set up the Hupenyu Ivhu (Soil is Life) Farmer Innovators’ group in 1989, and in 2014 his work was recognized with the Phiri Award for Farm and Food Innovators.

Search “Bouwas Mawara” at HarvestingRainwater.com for video and more from my 2016 visit.

Terraces

WHAT IS A TERRACE?

A terrace, sometimes called a bench, is a relatively flat "shelf" of soil built parallel to the contour of a slope (fig. 4.1). This is not to be confused with a retaining wall that may support the terrace of soil. Terracing creates *flat* planting areas for gardens, orchards, or native vegetation that will utilize the harvested water and stabilize the slope. And as you will see in the Tarahumaran Indian example at the end of this chapter, terracing can also check erosion, harvest soil, and recharge wells. This is an energy-intensive strategy requiring a good deal of soil and rock movement, so it is typically reserved for use on smaller sloped lots where space is limited, and the need for planting space will justify the work. A series of terraces creates a steplike effect that encourages more water to infiltrate into the soil than run down the slope, while helping control erosion. Terraces can be used on steeper slopes than berm 'n basins if stabilized with a retaining wall or dense vegetation on their downslope side, though such dense vegetation is often lacking in the dryland environment. Retaining walls can be beautifully simple, using only natural or salvaged stone, gravity, and the right angle and care in their installation to hold them in place—no mortar is needed. And the retaining wall, if no taller than 18 inches (45 cm) high, can double as a seating bench.

Fig. 4.1. Terraces stabilized with dry-laid walls made from salvaged concrete sidewalk pieces or "urbanite" in Pasadena, California. Designed and installed by La Loma Development Company.

Unlike berm 'n basins, terraces do not have depressions built into them, so in order to retain more rainwater and accumulate organic material, they need to be bordered by a wall or a berm. The terrace also spreads the water out more over the wider level surface so everything within is more evenly watered and less likely to drown.

This chapter discusses three kinds of terraces: a) earthen terraces without retaining walls, b) dry-wall stone or concrete-chunk retaining-wall-stabilized terraces, c) masonry-wall-stabilized terraces. I prefer the first two kinds of terraces, and provide instructions for building them. I do give a reference for masonry terraces, but am not really promoting them—especially if mortar is used, as I feel it's better to use porous dry-laid retaining walls, preferably with native, salvaged, or at-hand materials (fig. 4.2).

Fig. 4.2. Terraces stabilized with dry-laid stone walls and accessed via a whimsical stairway. Stonework by Goettling McGee, Inc., Seattle, Washington

How would you know which type of terrace to build? The slope and the look you want determine it. Only gradual slopes can handle terraces without retaining walls, and these terraces act a lot like stepped basins. Terraces with retaining walls are for steeper slopes; they are more work up front, but can be less maintenance down the road due to the stability of the retaining wall (it doesn't erode).

WHERE IS A TERRACE USED?

Of all the strategies in this book, this is the water-harvesting approach that *needs the most caution*. While terraces are used successfully throughout many parts of the world, the progressive failure of poorly built or poorly maintained terraces breaking down in a domino effect can cause severe land damage, probably worse than if they had not been built at all.[1] For this reason, this book limits its scope to backyard-scale terrace construction within backyard-scale watersheds. Here your chances of success are increased and your chances of failure (and consequences of failure) decreased.

I'm defining a *backyard application and scale* as one where:

- You are in control of your entire watershed and you have implemented strategie harvest or divert all potential upslope runoff before it enters your planned terra area.
  Reason: You do not want to risk unchecked or unforeseen flows from upslope blowing out your terraces. Clearing vegetation, diverting water, wildfires, and construction can all create or magnify erosive runoff.

- Both the slope on which you are constructing the terraces, and the slopes above and below the terrace work, do not exceed 2:1.
  Reason: Steeper slopes are far more challenging and risky locations to construct terraces, and should be left to experienced terrace builders, or those under the supervision of knowledgeable engineers.

- There are no sublayers of clay beneath the area where you plan to construct you terraces.
  Reason: Clay is soil's natural grease. If soil on a slope above a clay layer becomes supersaturated with moisture, you risk the chance of a localized landslide.

- Terraces are built at a scale that you can do yourself.
  Reason: You want structures that you can easily manage and maintain yourself.

If you want to tackle larger or more challenging sites, do so only with the supervision of an engineer and/or experienced stone mason familiar with local conditions and the utilization of terraces for harvesting rain in the soil.

Terracing is an energy-intensive strategy, and will cause much disturbance to the land when the work is being done. This disturbance will be slow to revegetate in drylands. So, this strategy is only recommended in areas of intensive use, such as back- or frontyard gardens or actively maintained agricultural land, that will provide the needed inputs to quickly vegetate/stabilize the terraces and maintain them.

A terrace is most effective when constructed on a gradual slope that has stable soil. The ratio of the amount of earth moved to the amount of terrace created decreases as slopes get steeper, making the work less practical and efficient. Terracing for agriculture is preferable at slopes of 10–18° (18 to 33% grade).[2] Nonetheless, in many parts of the world where arable land or space is limited, such as Cape Verde, the Andes of Peru, and parts of Southeast Asia, terraces are

common on slopes much steeper than 22˚ (40% grade).[3] In such systems rainfall is harvested within the terraces, and often creek or runoff water is directed through them for supplemental irrigation. I reference sources that cover such uses of terraces but the information I present here deals *only* with harvesting rain that falls directly on the terrace and the minor slopes between terraces that are built in a series.

Terraces are not appropriate in soils prone to waterlogging where rainwater infiltration could lead to saturated subsurface conditions due to the presence of layers—such as clay—that impede the movement of water down through the soil.

TOOLS AND MATERIALS

Tools: For earthen terraces you'll need: a level (appendix 1 provides options and instructions), a pointed shovel, and a pick or mattock. A backhoe comes in handy for larger-scale terrace projects where you have adequate access.

If constructing retaining walls for your terrace you will also need a hand tamper (see fig. 4.10 later), wheelbarrow, pry bar, stone mason's hammer, and sledgehammer.

Materials: Mulch to cover the surface of the terrace and its berm, seeds and/or live plants to vegetate the terrace, berm, and any areas of disturbance.

If you are constructing retaining walls, you will need angular stone or broken-up chunks of concrete sidewalks ranging in size from 12 to 24 inches (31–61 cm) long. Ready-made stone for dry-stacked retaining walls is usually available for purchase at your local hardware store, but try to find at-hand alternatives.

IMPLEMENTATION STEPS TO BUILD A TERRACE

SITING

Determine if and where terraces will meet your needs and if a retaining wall will be needed (fig. 4.3). As a general rule, the added support of retaining walls will probably not be needed if the terraces are located on well-vegetated slopes with stable soils, and they are constructed in locations with a slope of 3:1 (18° or 33% grade) or less, both above and below the terrace itself. It is your responsibility to assess whether the slope you are working on is stable. If you have any doubts about its stability, consult an engineer.

Fig. 4.3. Different strategies for different steepness of slope. Note that the retaining walls drawn in this illustration would likely need to be designed/constructed by experienced professionals due to the steepness of the slopes drawn. Note that slopes described in the text are appropriate for backyard applications. Dashed brown line denotes original slope.

If slopes are steeper than 3:1, build retaining walls.

Choose the general locations for your proposed terraces based on your site goals. Water-harvesting terraces are often used on smaller, sloped lots to maximize the amount of gardening and planting space. Use a level (see appendix 1 for options) to find the land contour in these locations, then mark the terrace locations with stakes, flagging, surveyor's spray paint, or a line scratched deeply into the soil.

Mark all the potential terraces you are planning to build now, in order to integrate them with one another. Unlike a series of berm 'n basins, a series of terraces should be constructed *starting from the bottom of a slope and moving up*. This is helpful because once you build the first terrace at the bottom, you will have a level terrace from which to work as you move upslope. Each terrace then helps stabilize the base of the terrace built above it. In addition, the topsoil removed during the construction of a higher terrace can be spread out on the terrace below to help build its soil layer.

Remember, however, to follow the overriding water-harvesting principle of starting at the top of the slope when you *plan* your work. While it is best to build

terraces from the bottom up, all other water-harvesting strategies planned for areas upslope of your terraces should be constructed before constructing your terraces.

SPACING AND APPROPRIATE SIZE

Determine the spacing and size of your terrace according to the type of terrace you decide to build, the steepness of the slope, and the depth of your soil. The terraces should be spaced and sized to harvest both direct rainfall on the terrace and runoff from the slope above, while ensuring the harvested water will not sit on the soil surface longer than 12 hours. If you want to calculate approximate size and spacing for a series of such terraces see box 4.1. See box 4.2 for calculating optimal terrace width based on slope. See figs. 4.4A, B to see where depth, width, and length measurements are taken.

Box 4.1. Calculating Approximate Water-Holding Capacity (Volume) and Spacing of Terraces

WATER-HOLDING CAPACITY OR VOLUME

The calculation process for terraces is generally the same as that used for berm 'n basins (see the previous chapter on berm 'n basins, boxes 3.2 and 3.3). The one difference, because the terrace is flat, is that the terrace calculation is adjusted to reflect the more rectangular shape (in cross section) of the terrace. Therefore you calculate the size, or water-holding capacity, of a rectangular terrace with the following calculation for volume:

VOLUME OF WATER-HOLDING CAPACITY (ft^3) = LENGTH (ft) × WIDTH (ft) × DEPTH (ft)

For example, you're planning to build a terrace that is 24 feet long, 8 feet wide, and 4 inches or 1/3 (0.33) foot in depth below the spillway.

Volume in cubic feet = 24 ft × 8 ft × 0.33 ft = 63.36 ft^3 (rounded up to 64 ft^3)

Multiply by 7.48 gal/ft^3 to convert to gallons:

Volume in gallons = 64 ft^3 × 7.48 gal/ft^3 = 478.7 gallons

You may also want to calculate the per-foot volume of your terrace. In some cases, you may not need this, as the constraints of a small backyard may determine the size of your terrace. However, in terracing a larger area with catchment area upslope, it will be useful for calculating spacing between terraces.

VOLUME IN CUBIC FEET PER 1 FOOT OF TERRACE = 1 (ft) LENGTH × WIDTH (ft) × DEPTH (ft) Volume in cubic feet per 1 foot of terrace = 1 ft × 8 ft × 0.33 ft = 2.64 ft^3 per 1 foot of length

Remember that the result does not include amount of water infiltrating the soil.

SPACING

If it seems possible to use terracing for water harvesting over a large area, with multiple terraces or other earthworks catching rainfall from a large slope, you may find this calculation useful. Once you've calculated the water-holding capacity of your terrace per foot of length, calculate its spacing related to the catchment area above the terrace.

SPACING DISTANCE (ft) = TERRACE WATER HOLDING CAPACITY (ft^3 per 1 ft length) ÷ (RUNOFF COEFFICIENT × RAINFALL FROM A LARGE STORM (ft))

Using the figure of 2.64 ft^3 per 1 ft length, assuming a runoff coefficient of 0.40 for a healthy Sonoran desert indigenous landscape (see runoff coefficients in box 3.3), and wanting to capture all the runoff from a 3-inch or 0.25 ft storm (3 inches ÷ 12 inches/ft = 0.25 ft):

Spacing distance = (2.64 ft^3 /1 ft length of terrace) ÷ (0.40 X 0.25 ft) = 26.4 ft spacing

See appendix 2 for metric calculations.

Box 4.2. Calculating Optimum Terrace Width

In dryland areas, you can calculate the optimum width of a terrace with the following calculation from Herman J. Finkel's *Semiarid Soil and Water Conservation*[4]:

WIDTH OF TERRACE = MAXIMUM DEPTH OF CUT IN THE SOIL ÷ THE DEGREE OF THE SLOPE

For example, on a 10% or 0.10 slope, if the maximum allowable cut is 1.5 feet, the width of the terrace would be 15 feet (see Fig. 4.5). The width is calculated as follows:

15 ft = 1.5 ft ÷ 0.10

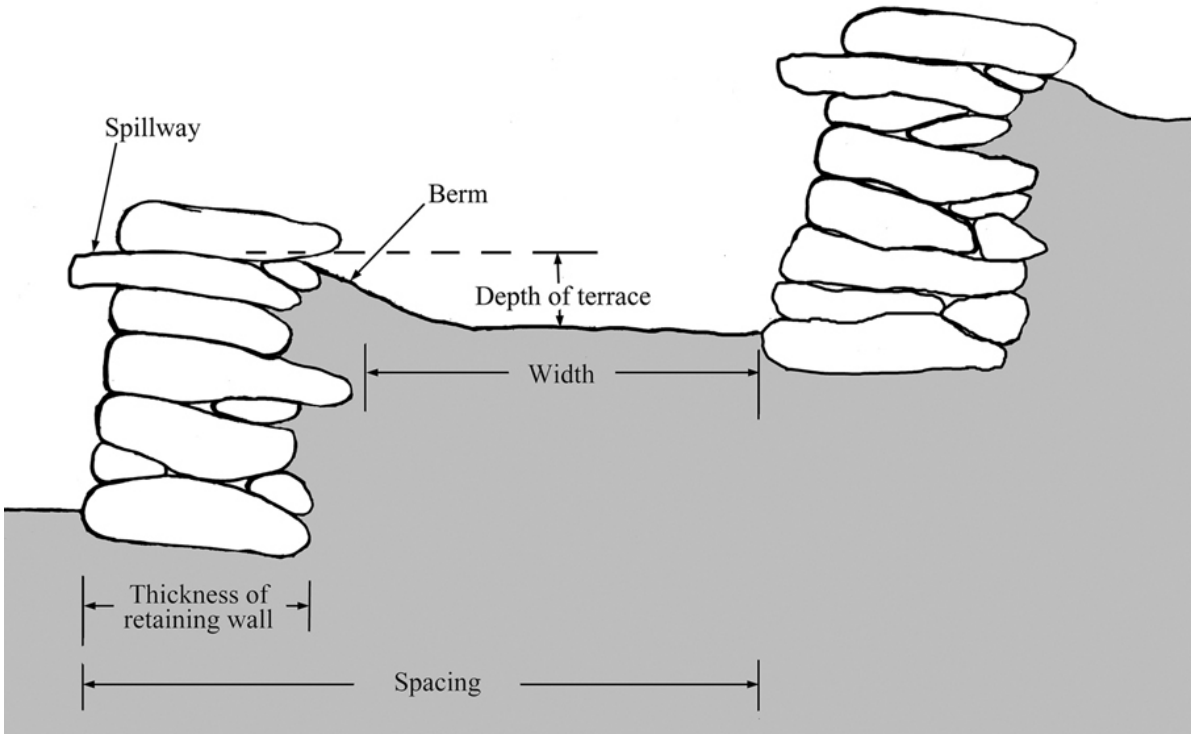


Fig. 4.4A. Side view of terraces showing components and basic features and measurements

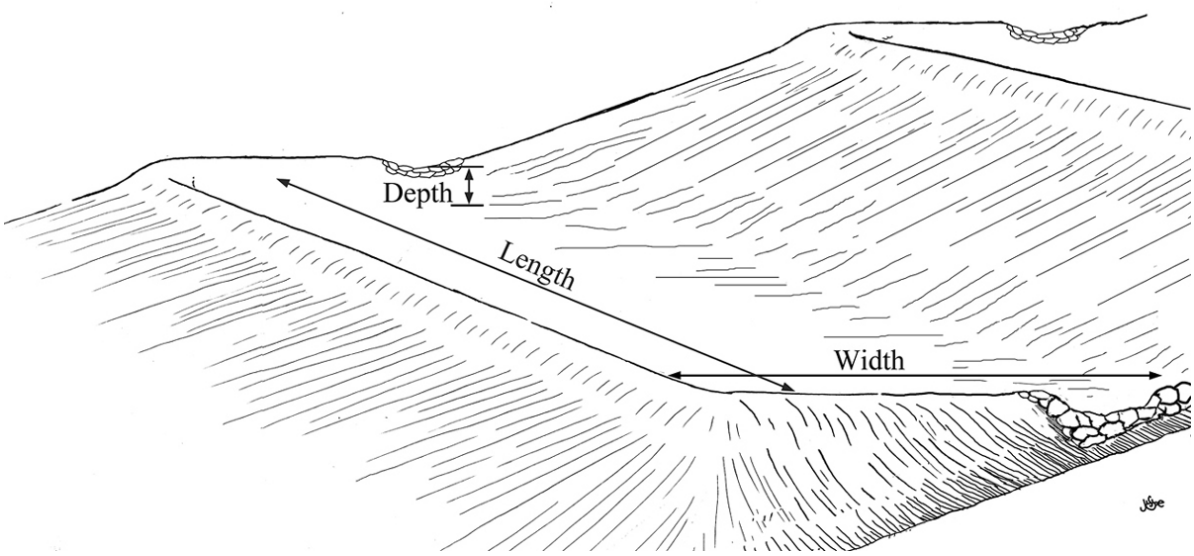


Fig. 4.4B. Earthen terrace without retaining wall showing depth (measured from level terrace surface to the top of the overflow spillway), width, and length measurements. Notice the berm and the stone spillways at the sides of the terrace's basin.

Retaining wall height

As shown in fig. 4.5, when building terraces with retaining walls, the height of the wall should not be more than twice the depth of the cut into the slope. The depth of the cut is limited by the depth of the soil, which is often shallow on steep slopes. In addition, follow the principle of starting small and playing it safe. The taller the wall, the more difficult the work, since you must use larger stones and lift them higher. Walls 2 feet (60 cm) or less in height are the easiest to build and also the safest. Do not exceed a wall height of 4 feet (120 cm) without the supervision of an experienced engineer or mason familiar with water-harvesting terraces.

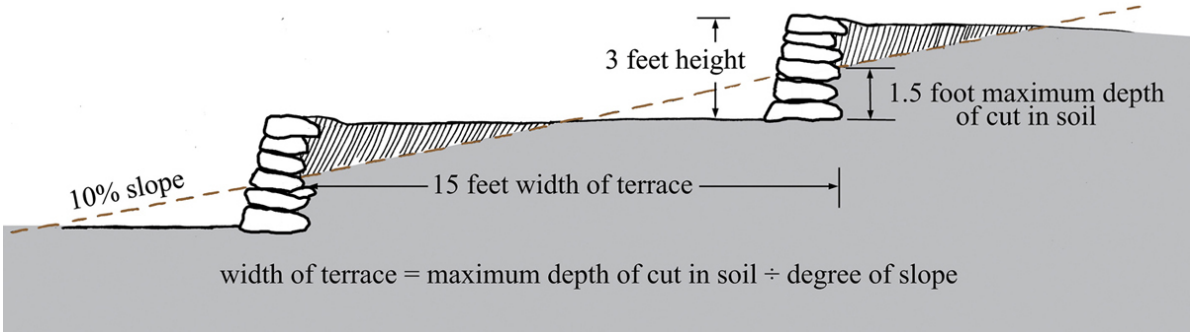

3 feet height
1.5 foot maximum depth of cut in soil
10% slope
15 feet width of terrace
width of terrace = maximum depth of cut in soil ÷ degree of slope

Fig. 4.5. The height of a terrace retaining wall should not exceed twice the depth of the cut made into the slope at the base of the wall. Here the cut is 1.5 feet, so the wall height does not exceed 3 feet.

Whichever style of terrace you build, you'll find the steeper the slope, the narrower the width of each terrace will be and the closer together a series of terraces will be (fig. 4.6). Box 4.2 gives a calculation for optimal terrace width based on slope.

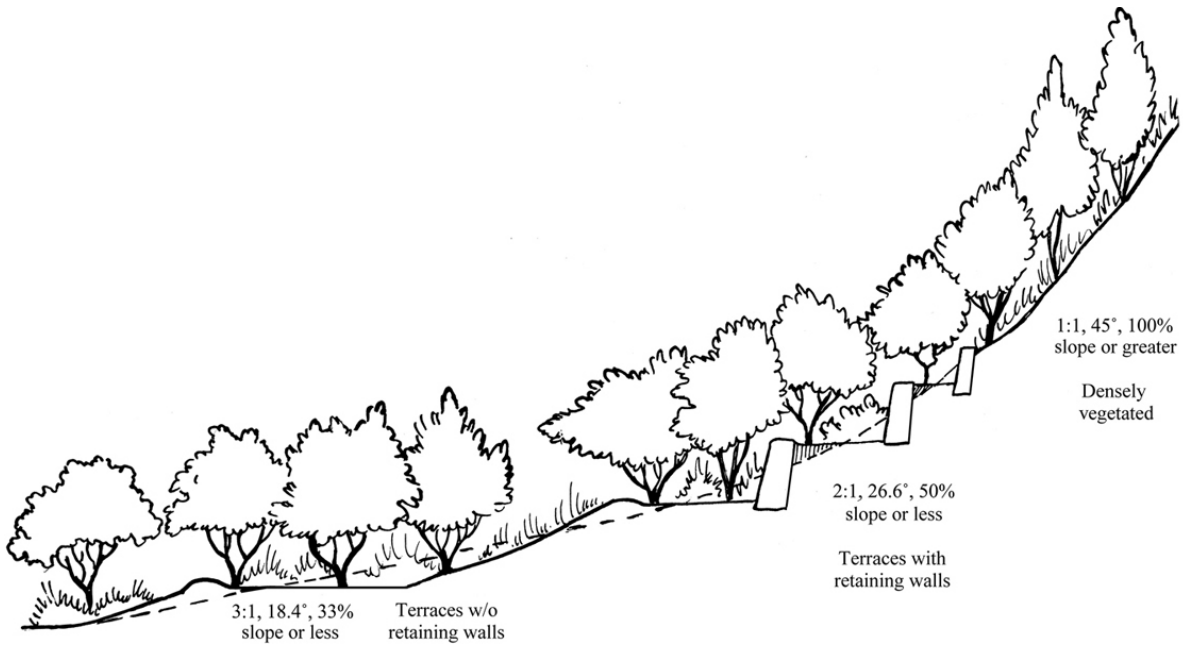


Fig. 4.6. Narrow terraces on a steep slope

Note: The heavier your rainfall and runoff, the more you should limit the size of a terrace and the extent of a terrace system to prevent it from being overwhelmed with too much water.[5]

CONSTRUCTION

This section is broken into two parts: terraces without, and terraces with, retaining walls.

Terraces *without* retaining walls

To construct a terrace without a retaining wall, dig into the slope to create the inner surface of the terrace and place the excavated topsoil to the side. (You want to eventually spread this fertile topsoil over the surface of your terrace, not bury it.) Continue digging, placing the excavated subsoil downslope to build up the outer surface of a level terrace bed. The deeper into the slope you cut and the farther out you fill, the wider the terrace will be. But make sure neither your digging nor the placement of your dirt results in slopes steeper than 3:1 above or below your terrace. Once you've made the terrace to the desired size, spread the topsoil that you placed off to the side back over the surface.

Use a level tool to make sure the bed of your terrace is level. Construct a raised, level berm along the outer edge of your terrace to help retain rainfall within the terrace, since the terrace itself will be level rather than concave (see fig. 4.7).

Without a berm, there is little water-harvesting capacity and no control of overflow, without which the terrace will erode. Compact the berm by tamping it with your feet. You can double its functions by making it wide enough to use as a path. Unless it is stabilized with rock, vegetation, or another material, I typically make the berm three to four times as thick as it is tall, ensuring good strength, a gradual slope, and a thicker girth less susceptible to an erosive blow out. The surface of the flat, finished terrace-bed area should be leveled but not compacted; you want rainwater to be able to infiltrate here.

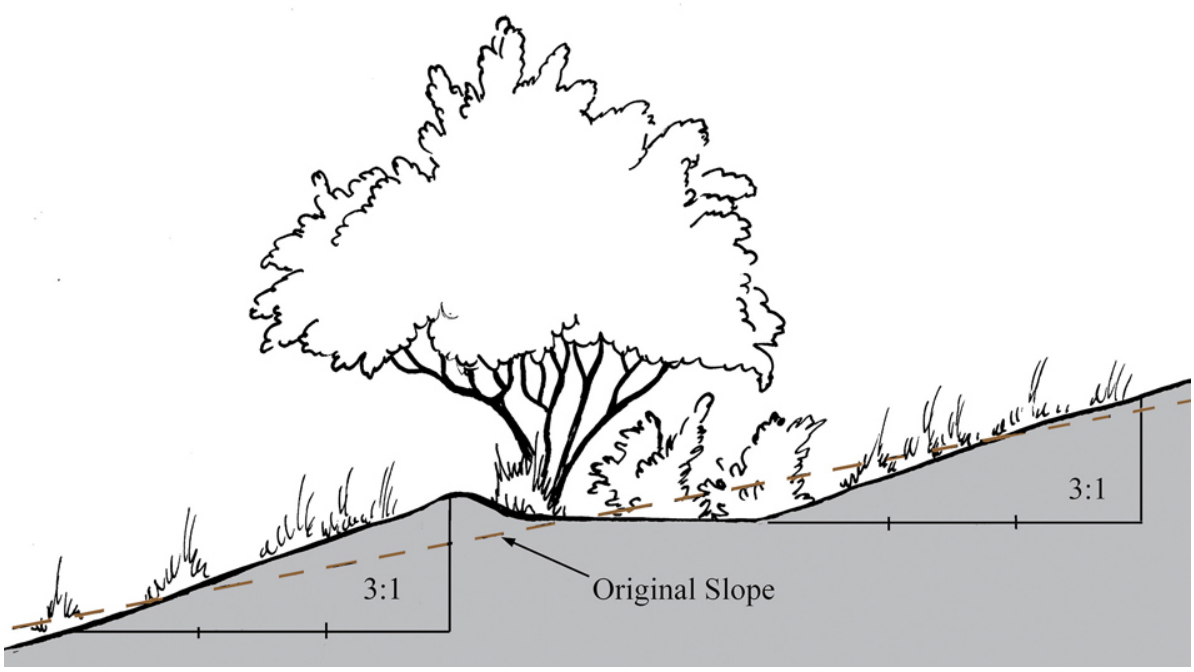


Fig. 4.7. A terrace without retaining walls. Such a strategy can be used on gradual slopes less than 3:1, 18°, 33%. However, care must be taken to ensure that the steeper slopes, created between the terraces by their construction, will not exceed a 3:1 slope; otherwise retaining walls will need to be constructed to stabilize the slope and structure.

Due to the sloping land present between the terraces, this style of terrace can harvest runoff from this slope and magnify the natural rainfall available to the terrace itself.[6] The slope must be well stabilized with vegetation to prevent excessive runoff and erosion of both the slope and the terrace. In addition, you must make sure terraces are properly spaced (using the calculations for terraces in box 4.1) so that the volume of anticipated runoff flowing from this intermediate slope will not exceed the capacity of the terrace, and potentially blow through your earthworks rather than infiltrate the soil.

Terraces *with* retaining walls

Before building retaining walls, check with local building authorities about guidelines or limits regarding their construction in your area. Different climates, soils, and seismic conditions can necessitate different requirements. See fig. 4.8 for an example.

Fig. 4.8. Terraces with sandstone retaining walls built by Raincatcher and San Isidro Permaculture harvest direct rainfall in Santa Fe, New Mexico. Although unseen, there is beneficial water-harvesting redundancy here. Roof runoff from canales (roof drains) is stored in an underground cistern and distributed via an automatic drip system to irrigate vegetation in dry times. A greywater system (shower, sinks, and clothes washer) adds additional irrigation water via infiltration trenches with perforated pipe.

Most municipalities require a permit for retaining walls over 2 feet (60 cm) high. Many also stipulate that walls over 4 feet (120 cm) high must be designed and their construction supervised by a licensed engineer.[7] This wisely encourages construction of a series of smaller terraces with low retaining walls, rather than one big terrace with a tall wall. At minimum you must meet local standards and codes.

Retaining walls are often built with a very wide foundation or footer, steel-reinforced masonry mortared in place, and weep holes or pipes that permeate the wall to allow drainage. For more information on steel-reinforced masonry

retaining walls, check *Basic Masonry* by the editors of Sunset Books, Sunset Publishing Corporation, 1995.

However, I find retaining walls constructed of dry-laid stone (no cement mortar) or broken slabs of salvaged concrete sidewalks often work better. Unlike a rigid wall, the loose rock structure is somewhat flexible, reducing horizontal pressure on the wall and absorbing some frost heave.[8,9] As a result, dry-stacked stone walls do not require as wide a foundation as would a conventional retaining wall. They save you the cost of cement and the negative environmental impact of its manufacture. Drain pipes are not needed since the dry-laid stone is naturally porous through the joints between the stones. This porosity is essential for the wall to work because it allows the release of excess soil moisture and hydrostatic pressure caused by water accumulating in the soil behind the wall. If this soil moisture and pressure were not released, the wall would fail. Since dry-laid stone retaining walls are my preference, the remainder of this section describes their construction.

Pick angular rock for retaining walls, not round river cobble. Angular rocks can better lock into each other, while round rock tends to want to roll or pivot. The rock should be durable. If it easily flakes or crumbles when struck with a hammer, it is too weak. More or less block-shaped stones with flat tops and bottoms make for easier, quicker setting. Rock size primarily ranges from 12 to 20 inches (31–51 cm) long for walls 2 feet (60 cm) tall or less, and from 20 to 24 inches (51–61 cm) for walls from 2 feet to 4 feet (60– 120 cm) tall. These lengths enable the rock to set deep enough into the slope and for backfill to firmly anchor or lock them in place. Smaller, flat shim and thicker wedge stones will be needed beneath or between the front or back of larger stones to level them in place. Small chinking stones will be needed to fill the gaps in wide joints between the larger stones. And smaller rock or rubble may also be needed to fill in some of the gaps between stones behind your wall before you backfill with soil.

You should begin at the base of your slope or along a section of the slope that is relatively gradual, allowing both a stable base for your wall and about a 4- to 6-foot (120–180 cm)-wide area you can clear for access, piling stone and tools, and maneuvering while you work. Create the “pad” or “platform” on which the retaining wall will be placed. To do this, dig out a level platform into the subsoil of the slope. Subsoil is the naturally compacted soil beneath the less compacted, more organic-rich topsoil. It is important to recognize the difference because if you do not build the base of your wall on well-compacted earth, the soil will later compress or settle and your wall will sink.

You want your platform to be about 4 to 12 inches (10–30 cm) wider than the planned thickness of the retaining wall—not the planned width of the terrace. The thickness of the wall should be from 12 to 20 inches (31–51 cm) for walls 2 feet (60 cm) tall or less, and from 20 to 24 inches (51–61 cm) for walls from 2 feet to 4 feet (60–120 cm) tall.[10] The taller the wall, the wider its base, and the larger its "batter" will be. A batter is a deliberately constructed lean of the wall back toward the slope to prevent shifting soil from eventually toppling the wall. Dry-stacked walls up to 2 feet in height should have a 5° to 10° batter into the slope. Walls from 2 to 4 feet in height must increase their batter to 15°.[11] (Fig. 4.9 shows a diagram of dry-laid stone retaining walls.)

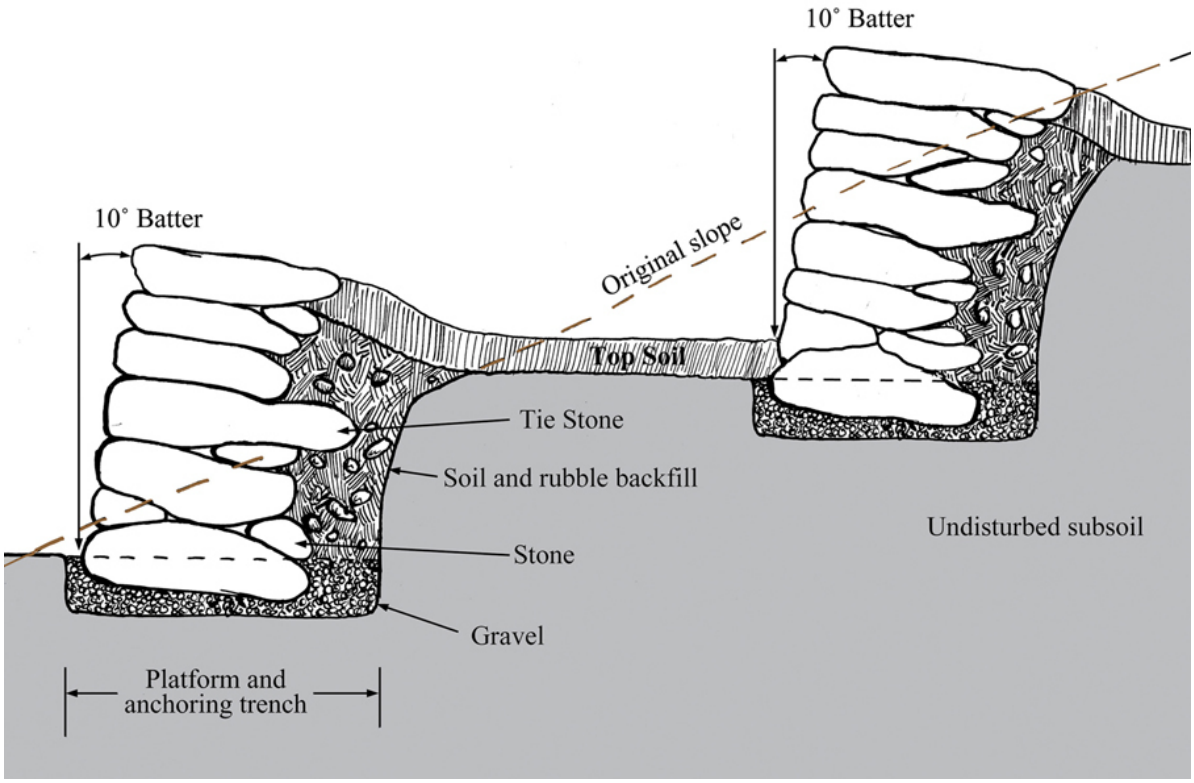


Fig. 4.9. Elevation view of two dry-laid stone retaining walls and associated terraces. The "tie" stones or "dead-men" are long stones randomly placed in the wall to reach further back into the backfill to better tie or anchor the wall in place.

With your platform established, dig an anchoring trench for the wall. This means digging down an additional 6 inches (15 cm). The trench will hold both a 2-inch (5-cm)-thick base layer of open-graded, angular gravel and your wall's first course of stone, so the gravel and the bottom part of the stones will be beneath

grade. If the soil drains poorly due to heavy clay soils or for some other reason, you can improve drainage and stability by digging the trench deeper and adding proportionately more gravel in the bottom of the trench.

Stockpile your excavated dirt and rubble to the side to use later to fill in behind your retaining wall, and *save topsoil in a separate pile* to use later for the upper layer of the terrace.

Compact the gravel within your anchoring trench by tamping it with your feet or a tamper (fig. 4.10A, B), then carefully lay and set the first course of stone *firmly* in place on the gravel. Use your heaviest stones for the base of your wall. The upper surfaces of all the stones should be pitched slightly toward the rear of the wall, further reinforcing the wall's batter or lean into the slope.[12] Add or remove gravel beneath the stone to set it to the desired angle. Lay the stones of your wall as close against one another as possible, *plugging any holes between them with smaller rocks to hold back the soil.*

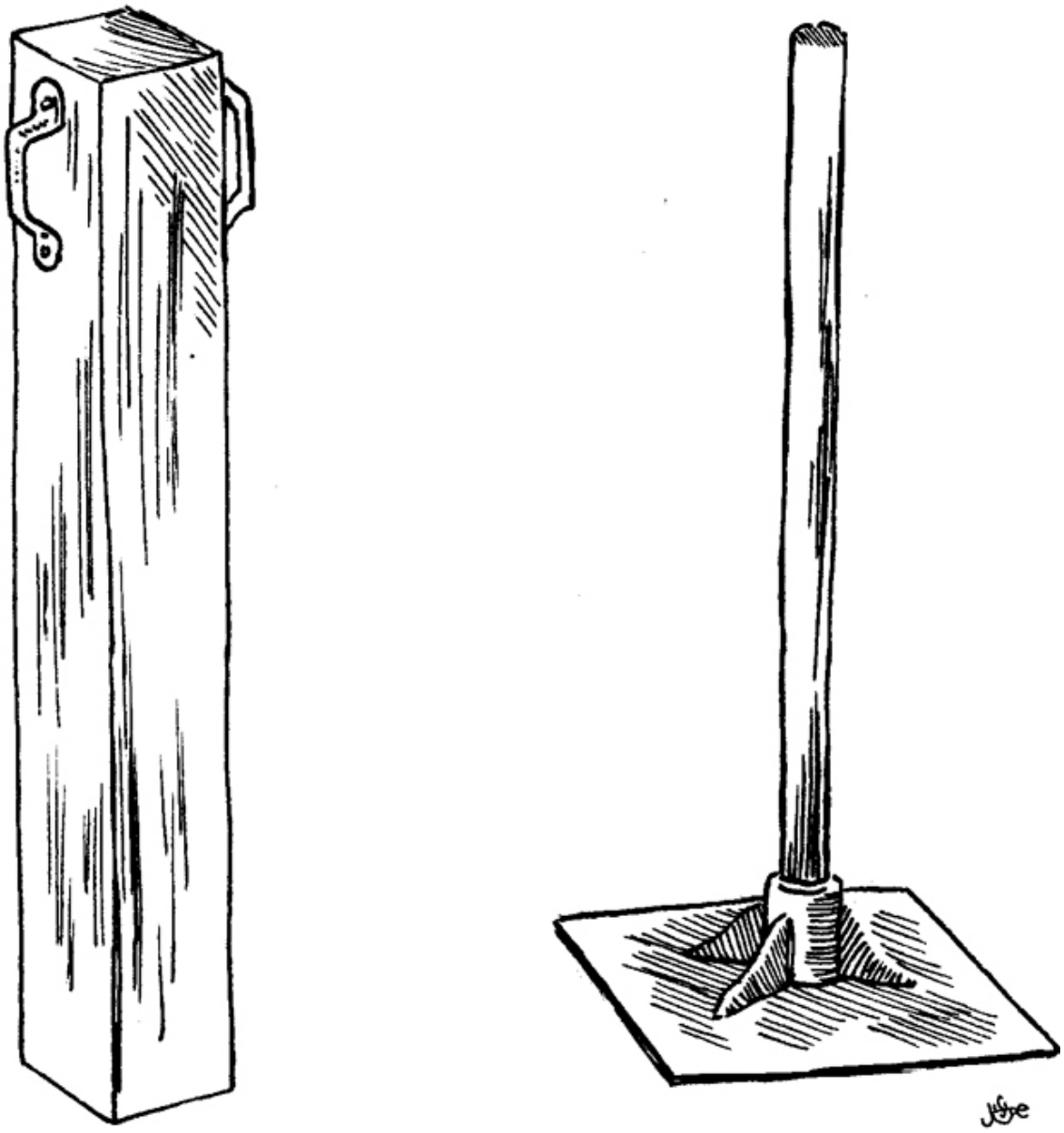


Fig. 4.10A. A homemade 4 x 4 tamper and a purchased hand tamper

Fig. 4.10B. You hold the handle or handles and tamp the earth or gravel with the flat bottom of the tamper.

Next, backfill between the inside of the wall and the cut in the slope. I live in a warm climate and always use compacted subsoil as my backfill material (see box 4.4 for cold climate considerations). Compaction of the backfill material is key,

because you do not want a loose backfill that will too quickly drain harvested water through the backfill and out the terrace wall (box 4.3). Such rapid draining would result in erosive pipelike holes forming through the backfill and even the soil beneath your terrace's basin, converting your terrace from a water harvester into an erosive and leaky sieve. Compact the backfill using a hand tamper and then a metal rod or the handle of a mini sledge-hammer to fill any hidden voids and compact the soil between, behind, and under your stones. Nontoxic rubble, such as broken up concrete, pieces of brick, and rock fragments can be added to the backfill mix behind your terrace wall for convenient on-site use of these "waste" materials.

Box 4.3. Landscape Fabric: An Optional Net Between a Terrace Wall and Its Backfill

Some builders of water-harvesting terraces such as San Isidoro Permaculture in Santa Fe take the additional precaution of laying either landscape fabric, a mat of coconut fiber, or three layers of burlap between their terrace walls and the compacted soil backfill. The fabric acts as a water-porous net, which, along with the small rocks used to plug holes between terrace wall stones, helps ensure backfilled soil will not erode through the terrace wall.

Box 4.4. Considerations for Terrace Walls in Cold Climates

I do not have any terrace-building experience in cold regions, and have used only soil as a backfill. Soil is also the chosen backfill among my water-harvesting, terrace-building friends in colder Santa Fe, New Mexico (7,000 feet elevation with average January high temperatures of 40°F (4°C) and lows of 19°F (-7°C)). But for still-colder regions, references on building dry-stacked retaining walls recommend a backfill of gravel with landscape fabric first laid against the cut dug into the slope.[13,14] The gravel improves drainage and the landscape fabric prevents the gravel from becoming clogged with sediment and soil. Together, the gravel and fabric form a protective layer that prevents frost-heaved soil from pushing through your backfill and shoving out your wall.[15]

Note: The resources I've consulted for cold-region retaining-wall construction do not specifically address retaining walls for water-harvesting terraces. Thus I worry that a gravel backfill, if not adequately covered with a compacted berm of soil, may too quickly drain water harvested within the water-harvesting terrace, leading to erosion of the structure. Therefore, anyone considering constructing this strategy in a cold region should first consult with local experts.

Sweep soil or gravel off the top surface of the first course so the next course will rest directly on stone. Then repeat the process for your next layer of rock. And remember:

• Offset vertical joints with every new course of rock by placing a whole rock over the joint between the two rocks below it. This greatly adds to the strength and stability of the wall.

• Maintain your batter.

If your terrace wall needs to rise above the level of the cut you made into the slope, use your stockpiled earth to create a higher mound on the slope against which you can build your wall. Thus, the terrace surface is built up in layers as each course of stone wall is laid to retain it. Then, use your stockpiled topsoil to construct the uppermost layer of your terrace and make it level.

If building a series of terraces, remember that you are working from the bottom up and you want to work with gravity. So when you cut a new platform into the subsoil of the slope for your next higher retaining wall, use the dirt you excavate to build up the soil level in the preceding terrace below (fig. 4.11).

Fig. 4.11. Building terraces starting at the bottom of the slope and working up

Course by course, build your terrace wall to the level you want your terrace soil to be, and then above.

Now, construct your *terrace berm*. The top course of the stone wall will act as the outer edge of your berm, so it should rise at least 5 inches (12.5 cm) above the level of your terrace, and more if this terrace wall will include a spillway (see next subsection). Use large, flat-topped capstones for stability and to serve as a potential footpath. Then add and compact dirt along the inside edge of the wall to create

the earthen portion of the berm. Without a berm there's no control of overflow, and the terrace will erode.

If in making your terrace you created a slope steeper than 3:1 above it, stabilize that slope with another retaining wall.

And don't forget to make your terraces accessible. Build in steps for an access path or create a ramp at the end of your terrace for wheelbarrows and other equipment, making sure the top of the ramp is high enough to prevent it from becoming a drainageway for the terrace.

For more detail on dry-stacked stone retaining walls consult David Reed's *The Art and Craft of Stonescaping: Setting and Stacking Stone*. For tire retaining walls, see box 4.5.

Box 4.5. Tire Retaining Walls

If you want to investigate the use of salvaged tires rammed with earth as a retaining wall material see the how-to guide, *Earthship, Volume III: Evolution Beyond Economics* by Michael E. Reynolds, Solar Survival Press, 1993. EarthshipGlobal.com

LOCATION AND CONSTRUCTION OF APPROPRIATE SPILLWAY(S) FOR OVERFLOW

Directions from this point on apply to terraces both with and without retaining walls.

The spillway is the planned overflow route for excess water to safely flow over the terrace berm. A spillway is a low point in the berm, dipping down to about half the berm's height. For a typical backyard terrace, the berm might be 10 inches tall, so in that case the spillway would be 5 inches (12.5 cm) below the berm's top. I recommend designing for no more than a 5-inch (12.5-cm) depth of water storage capacity on the surface of a terrace. This maximum 5-inch depth helps ensure that the terrace does not retain too much water, which could supersaturate the soil, leading to failure of the terrace.

Make your spillway and overflow route large enough to handle all surplus water. Thus the overflow outlet should be at least as large as the terrace's water inlet. A berm's spillway should be at least twice as wide as the berm is tall, with a minimum spillway width of 12 inches (30 cm). Narrower spillways are more likely to clog with debris.

If you have a series of terraces, align the spillways from one terrace to the next in a zig-zag or staggered pattern. This will help spread overflow more evenly across

the terraces rather than shortcutting the flow of water straight through them (fig. 4.12).

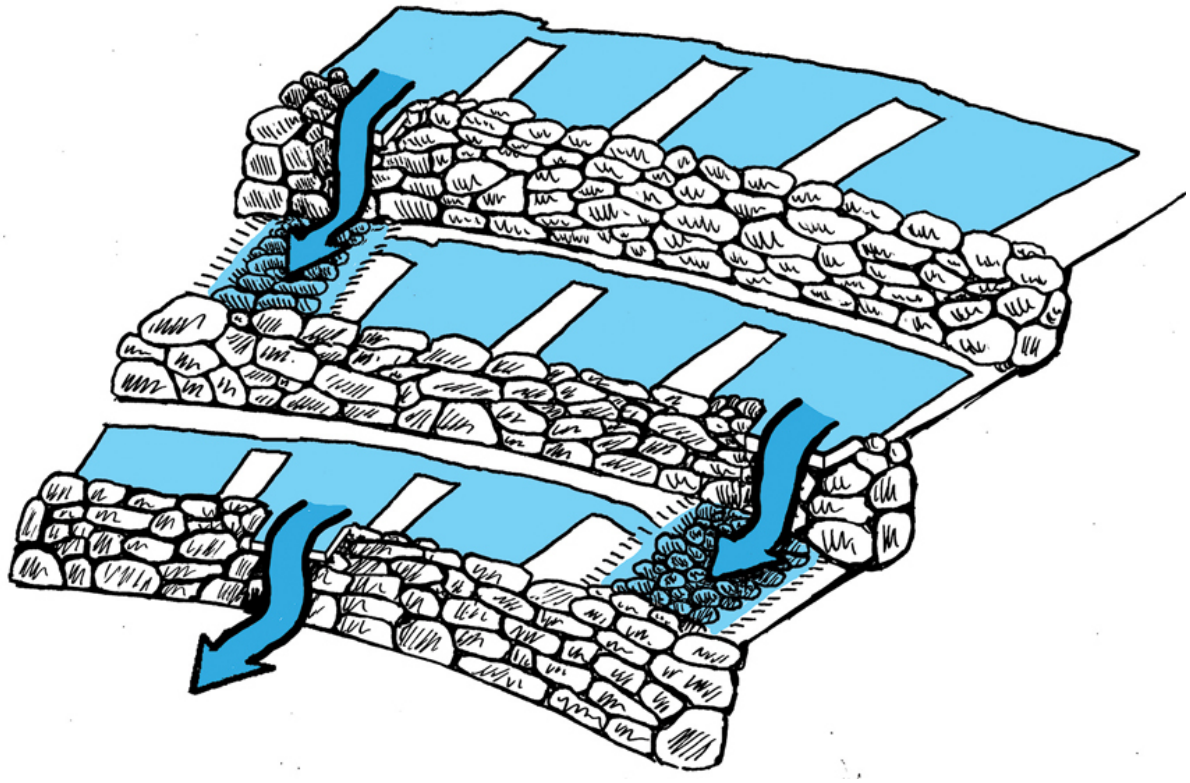


Fig. 4.12. Terraces with dry-laid stone retaining walls and zig-zagging overflows spreading and infiltrating more of the water's flow. Note that these terraces are divided into sunken planting beds.

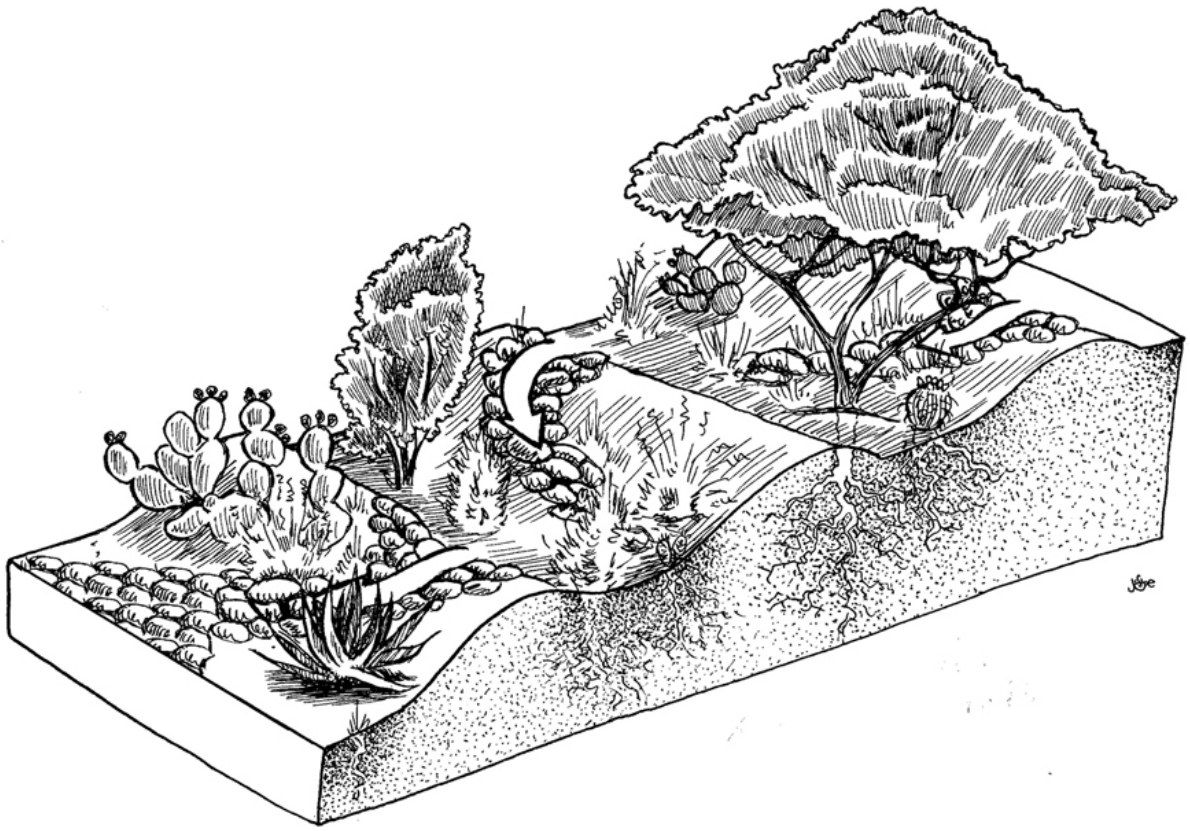


Fig. 4.13. Diversion swale overflows stabilized with rock-mulch rundowns. See chapters 9, 10 for more

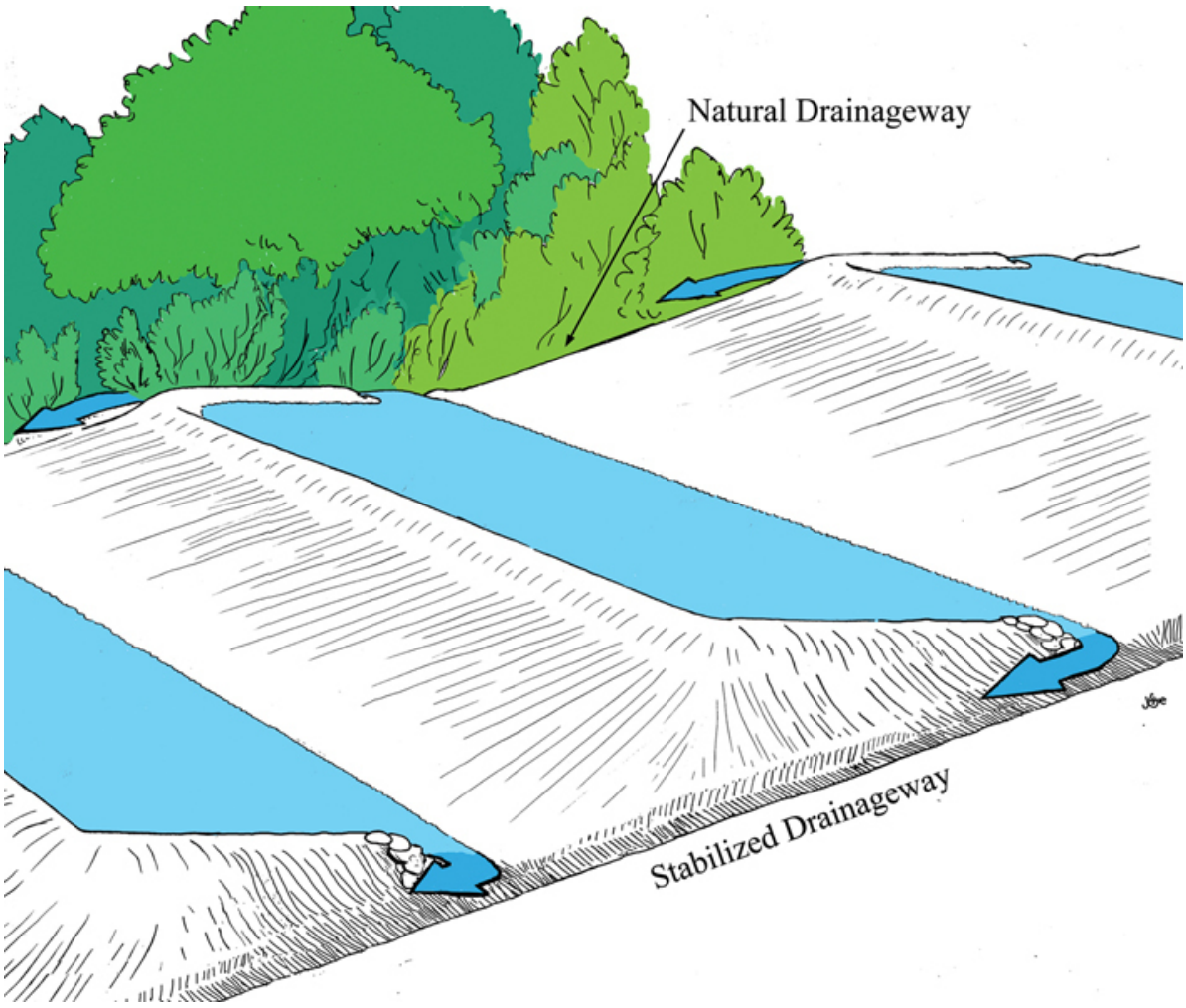


Fig. 4.14. Earthen terrace overflow directed to both a natural drainageway stabilized with vegetation, and a constructed stabilized drainageway

Between terraces that are built without retaining walls, a spillway from the upper terrace can be extended diagonally downward to become a diversion swale (see chapter 9) to connect the upper terrace to the next lower one (fig. 4.13). This will lessen the slope of the channel and reduce the speed of flowing water. Overflow can also be directed to a stabilized central drainageway (fig. 4.14).

Whichever terrace system you use, all spillways and the drainageways they flow into should be *stabilized*. Christopher Barrow, in his book *Alternative Irrigation: The Promise of Runoff Irrigation*, recommends using:

• Dense grass to stabilize spillways and drainageways on slopes of less than 15% (9˚) as long as the grass is protected from drought, brushfires, and livestock damage

• Rock for slopes between 15 and 20% (9–11˚)

• Stepped concrete and masonry if slopes are greater than 35% (19˚) to prevent erosion[16]

At the base of your spillway, place a stabilized apron or platform to disperse the force of the outflow. Make your apron at least as wide and as long as the width of your spillway channel.

See "rock-mulch rundown" in chapter 10 for more.

PLANTING YOUR TERRACE

Vegetation is a key element of any terrace system. Roots hold and stabilize the soil. Fallen leaves act as a green manure increasing humus and fertility. Transpiring plants utilize the harvested water, reducing the hydraulic pressure that infiltrating water exerts on hill slopes and retaining walls. Plant stabilizing perennial species to cover the slopes between terraces, spillways, areas abutting the retaining wall, the area just downslope from the flat terrace, and the berm itself. Maintain these stabilizing perennial plantings even if your primary use of the terrace is as a garden of annual plants. Limit your annual plantings to the level area within the terrace.

Focus on growing sheltering, low-water-use trees. Avoid planting water-demanding vegetation in dryland environments in general, and in areas of less stable soils in particular. By sticking to low-water-use species, you ensure that the rain falling naturally on the slope will be sufficient to support a well-established plant. This reduces water use and avoids the need for supplemental irrigation, which could destabilize the slope. See chapter 11 on vegetation for more tips.

Where your climate permits, tuck moss and other plantings between the rock of your retaining walls for more anchoring effect and a wonderful flow of vegetation springing over and from the rock (fig. 4.15).

Fig. 4.15. Vegetation between retaining-wall rocks. Stonework by Goettling McGee, Inc., Seattle, Washington.

MAINTENANCE

Check your terraces periodically, especially during and after storms, to make timely repairs, learn what works, and see how vegetation responds.

Make necessary repairs and adjustments, which could include: resetting loose or fallen rock, stabilizing eroding spillways, reinforcing berms, clearing debris from spillways, adding mulch to terrace basins, and replanting.

Good maintenance is vital, as the progressive failure of a series of unmaintained terraces can cause severe land damage. Watersheds above terraces must also be maintained to prevent unchecked and excessive runoff from blowing out the structures below. Keep watersheds well vegetated.

MULTIPLE FUNCTIONS OF TERRACES

LOW TERRACE WALLS AND TERRACES AS STEPS

Pathways that run up and down slopes typically become eroded drainage-ways. Creating terrace-like steps within these pathways, either by placing check-dam-like stone terrace steps or wooden railroad-tiesteps across the path can help stabilize the trail and reduce erosive runoff (fig. 4.16).

Fig. 4.16. A once-eroded path repaired with terrace-like steps stabilized with rock. Saguaro National Park West, Tucson, Arizona.

LOW TERRACE RETAINING WALLS AS BENCHES

Terrace walls 16 to 18 inches (41–46 cm) high double as seating benches.

TERRACING AS INFRASTRUCTURE FOR COMMUNITY WATER MANAGEMENT

In the mountain village of Huaynacotas, Peru, an intricate system of interlinking terraces, dating back to the time of the Incan Empire, still functions as a communally managed water-distribution system based on equitable distribution of resources (fig. 4.17). For an inspiring account of how it all works, read Paul Trawick's "Trickle-Down Theory, Andean Style: Traditional Irrigation Practices Provide a Lesson in Sharing," *Natural History*, October, 2002, pages 60–65, or his book *The Struggle for Water in Peru*.

Fig. 4.17. Terraced fields in Peru. Credit: Windsor Cousins

URBANITE TERRACE WALLS TURNING WASTES INTO RESOURCES

Urbanite—salvaged pieces of concrete pavement— is a great urban material for dry-stacked retaining walls. La Loma Development Company in Pasadena,

California, has mastered this material's reuse with high-craft installations (figs. 4.18A and B, and 4.19) that are in high demand. Combined, their urbanite projects from 2005 to 2012 removed a total of 16 million pounds (7 million kg) —or over 4,000 cubic yards (3,000 m^3)—of concrete from the waste stream, while enhancing the landscapes of residences, parks, schools, and businesses. People love this. Every year since 2012, La Loma's volume of completed urbanite projects has increased by five fold.

Fig. 4.18A. Retaining walls, driveway, and stairs are all made from urbanite—salvaged pieces of concrete pavement. Retaining walls are dry stacked without mortar. Urbanite in driveway and stairs is mortared. Designed and installed by La Loma Development Company in Pasadena, California.

Fig. 4.18B. Urbanite retaining walls, driveway, and stairs. Designed and installed by La Loma Development Company.

Fig. 4.19. Extra-long "tie stone" pieces of urbanite (see fig. 4.9) within a dry-stacked urbanite terrace wall create steps from one terrace to another. Designed and installed by La Loma Development Company in Pasadena, California.

REAL-LIFE EXAMPLES OF TERRACES

TERRACE BUILDING OF THE TARAHUMARA INDIANS—SIERRA MADRE, MEXICO

In 2002, while seeking examples of indigenous water-harvesting traditions, I visited the Tarahumara village of Wajurana, high in Mexico's Sierra Madre overlooking majestic Copper Canyon. I was guided by Juan Daniel Villalobos, the local director of *K'etami Wasar'a*, which means "our sustainable farmland" in Tarahumara. On these beautiful though marginal lands, erosion is often severe and water is scarce. Overgrazing and excessive timber cutting in growing pastoral communities compounds land and water problems.

Juan Daniel showed me a community practice that was reducing erosion and enhancing local water resources: numerous stone "*trincheras*" built throughout the village. *Trinchera* is a Spanish term for both stone-wall-reinforced terraces and check dams. Averaging 5 feet (1.5 m) high and ranging from 30 feet (9 m) to over 300 feet (91 m) long, their construction has helped the villagers reclaim a hectare of eroding land and annually harvest a significant amount of stormwater runoff in the soil. These simple structures have made it possible for many households to set up subsistence gardens, heirloom-fruit-tree orchards, and stands of native timber trees (see figs. 4.20 and 4.21).

Fig. 4.20. New trinchera and field at Rowerachi, Chihuahua, Mexico, in 2002. Note the batter or lean of the wall into the slope. Credit: Barney Burns.

Fig. 4.21. Old trinchera and field at Rancho Newatabo, Chihuahua, Mexico, in 2002. Apple trees to left of photo are planted among another series of lower trincheras. Credit: Barney Burns.

Whether used as a terrace or a check dam, the construction of trincheras is virtually the same. What differs is placement. Terraces are built on eroding slopes outside of drainageways. Check dams are constructed within eroding drainageways. These trincheras are hand-built during traditional communal work parties. All participants are paid with food as they improve existing structures and create new public infrastructure. Each household builds an equal section of the trinchera. The combined hands can accomplish in two hours what one person would need eight days to complete. Once built, it takes one to three years for trincheras to naturally collect a level bed of soil upslope, converting eroded land into fertile gardens. Trincheras built in the Sierra Madre have remained intact for over 500 years.

For over 10 years, Juan Daniel has worked with *K'etami Wasar'a* helping plan and construct trincheras and plant gardens in villages. Village leaders determine

where and when they want to build. Juan Daniel works with Native Seeds/SEARCH and the Catholic Church to provide food for work parties, transport rock, and purchase vegetation-protecting fencing.

Juan Daniel started small, helping establish one trinchera garden in the village of Roguerrachi. Interest spread. Soon there were 15 gardens, then other communities came forward. Two hundred gardens have since been created. Where water is abundant, gardens grow annual vegetables. Where water is scarce, deeper-rooted fruit trees are the predominant crop. Most receive supplemental water from nearby springs, but in the drier areas some gardens and orchards subsist entirely on rainfall.

The trinchera gardens have improved the health of both land and people. A few years ago a 100-foot (30-m) deep well dug in Wajurana yielded no water. After trincheras were built, water appeared in the well. Though not enough to pump, there was enough soil moisture for the roots of vegetables and fruit trees to tap. Some families produced enough food and crafts to give up their jobs outside the villages and meet most needs within their communities.

This pattern can be replicated anywhere—plant local rains in local soils so more life and livelihoods can grow.

See "Trinchera Tradition in the Sierra Madre" by Barney Burns, *Seedhead News*, Fall Equinox, 2002, Native Seeds/SEARCH newsletter.

TERRACED CISTERN STEPS, GARDENS, AND MORE – SEATTLE, WASHINGTON

Residents of the densely populated, urban neighborhood of Belltown in downtown Seattle (average annual rainfall of 36 inches or 914 mm) have long been surrounded by concrete and glass. But a transformation is occurring. The residents came together in the mid 1990s to organize under the name of Growing Vine Street. Their goal: to turn the entire eight-block length of Vine Street into a street park—a parade of art and nature that reintroduces the hydrologic cycle to the urban core.

Their plan was to direct stormwater runoff from surrounding buildings to fanciful cisterns and a new urban stream meandering through various earthworks running the street's entire length (fig. 4.22). The new cisterns and stream now passively irrigate numerous plantings along the watercourse. And these plantings naturally biofilter many of the water's impurities so it can be released directly into

Elliot Bay below without passing wastefully through the city's conventional water treatment facilities, as was the case with the old below-ground stormwater pipes.

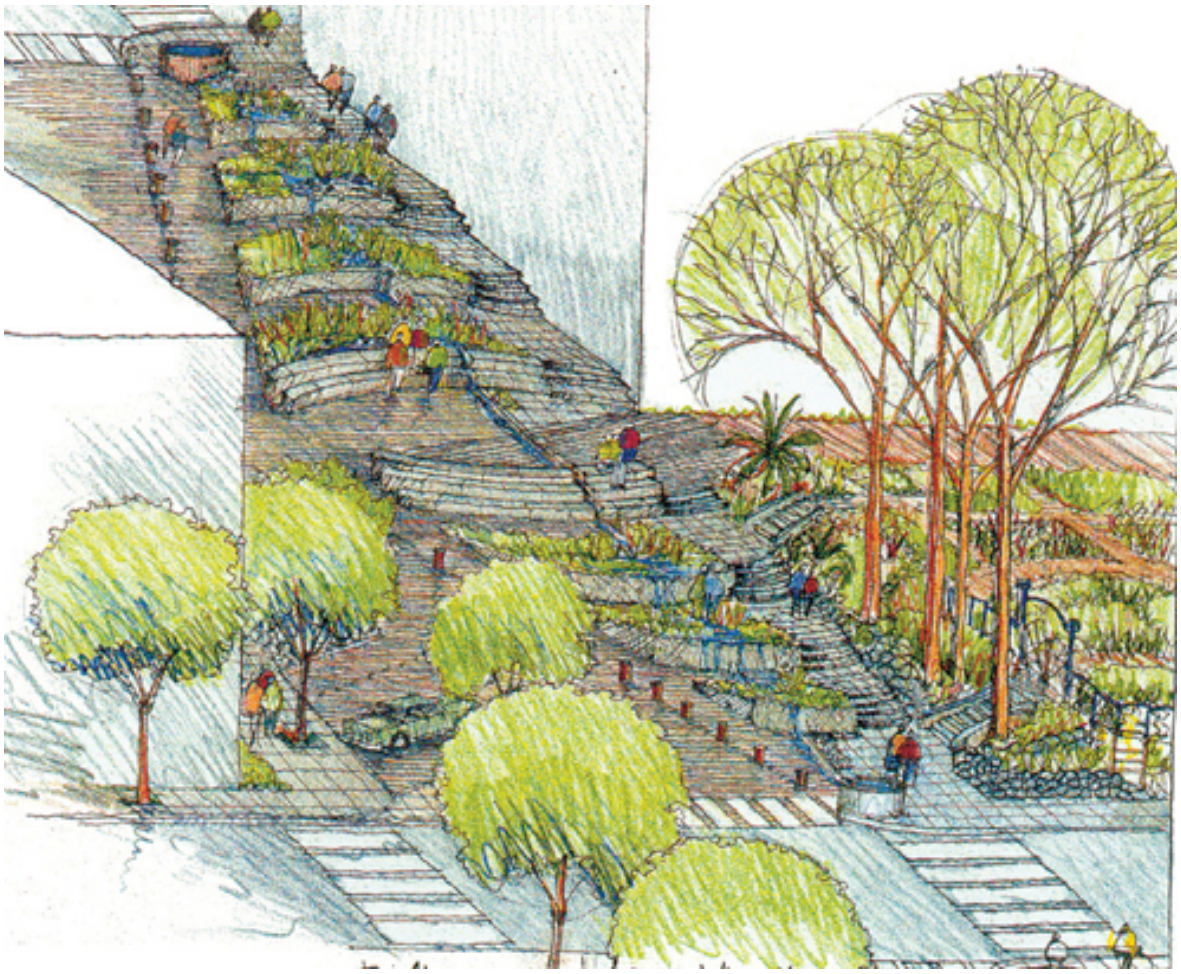


Fig. 4.22. Bird's eye view looking down Vine Street from Fourth Ave. to Third Ave., in Seattle, Wasington, showing the gardens, watercourse, narrowed street, and cisterns

Terraced planters are ideal here due to the slope of the street, the urban public space, and the canyon-like effect from the buildings. The terraces create level planting areas where before there were none, and they meander into the street, causing traffic to slow down. Along walkways, the terrace walls double as seating benches, decorated with colorful mosaics and sheltered with canopy trees. And gravity pulls the water from the mesa-like rooftops to spring-like cisterns, an old-fashioned hand pump within the garden, terraced planters, and the abundant plantings, until the overflow water empties into a small jade pool before merging with the waters of Elliot Bay.

A thriving community garden; historic cottages housing artists in residence; hand-shaped cistern; air-cleaning and noise-buffering "acoustic" trees, shrubs, and vines; and a series of large terraced planters called the Cistern Steps are already in place with more to follow (figs. 4.22 - 4.26). The result is a dynamic community green space where slowing the flow of traffic, water, and people has resulted in the area bursting with life and its celebration.

Fig. 4.23. The Beckoning Cistern and terraced planters. This 10-foot (3-m) high, 6-foot (1.8-m) diameter metal culvert cistern/sleeve reaches upward, capturing roof runoff through the hand's index finger and sending overflow out its thumb. The overflow water is then caught by a series of terraced planters. Terrace walls double as seating benches.

Fig. 4.24. View of the Beckoning Cistern from across the street. A faucet enables neighborhood gardeners to utilize the cistern water to irrigate the adjoining plantings.

Fig. 4.25. Continuing down Vine Street in Seattle, Washington, are more stepped terrace planters with meandering water channels and spillways. Photo: Britt Retzlaff Brennan.

Fig. 4.26. Close up of the stepped terrace planters with meandering water channels and spillways. Photo: Britt Retzlaff Brennan.

For the complete Growing Vine Street story and many more images see GrowingVineStreet.org.

CHAPTER 5

Infiltration Trenches

WHAT IS AN INFILTRATION TRENCH?

Sometimes called a soakaway, dry well, or a pumice wick, an infiltration trench is a trench or basin filled with porous materials including open-graded, angular gravel; pumice stone; or rough organic matter such as straw or bark. These materials have ample air spaces between them that allow water to infiltrate quickly into the porous material and percolate into the root zone of the surrounding soil, while creating a stable surface you can walk on, run across, or ride over with a bicycle. (See figs. 5.1 and 5.2.) Thus, infiltration trenches can be placed alongside impervious driveways and patios to harvest their runoff while simultaneously extending the pedestrian-accessible space along such hardscapes. Infiltration trenches can address the problem of "too much water in too small an area" and are especially useful for redirecting, holding, and subsequently infiltrating runoff from roofs and other hardscape in small yards. Infiltration trenches can be used for localized watering of adjacent plants to encourage deeper, more drought-tolerant root growth—these include deep-pipe irrigation and rock-tube irrigation. And, the source of that water can be rainwater or high quality air-conditioning condensate, which can be of considerable volume in humid seasons and climates, as explained in the section on multiple uses of infiltration trenches.

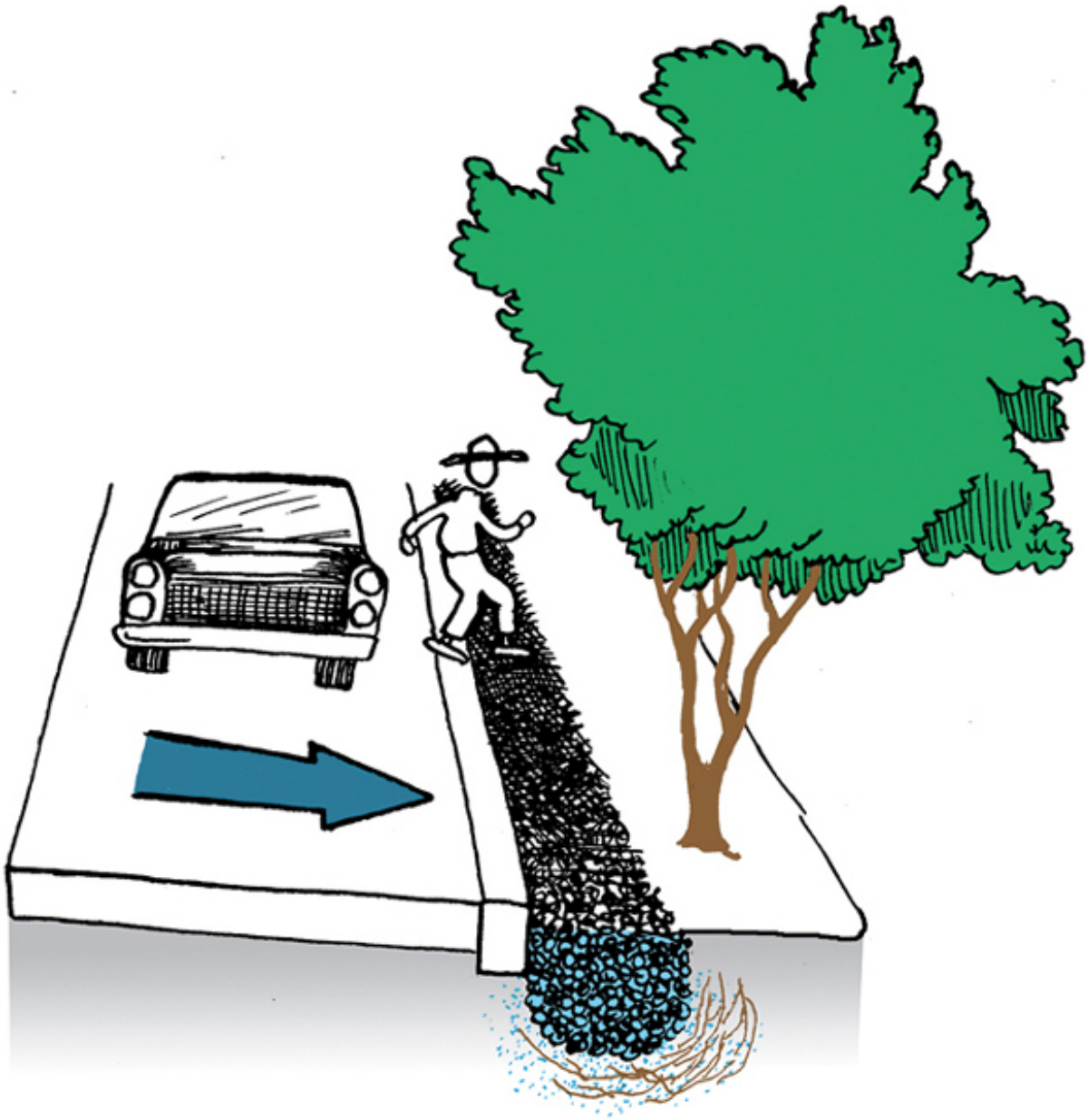


Fig. 5.1. A pipeless infiltration trench beside a driveway

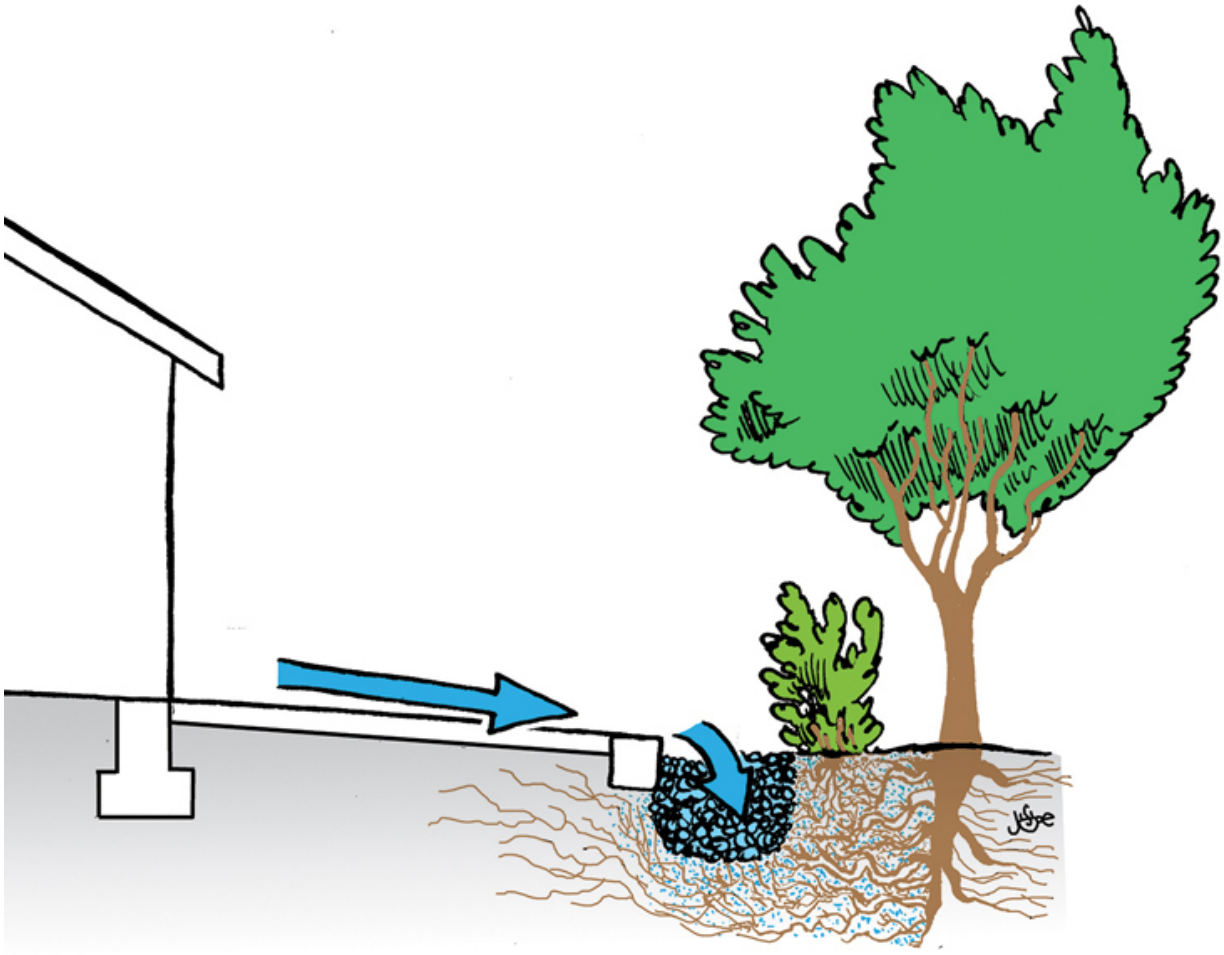


Fig. 5.2. Infiltration trench infiltrating intercepted runoff from a roof and patio

An infiltration trench can be constructed with or without pipe placed horizontally within the porous material that fills the drain. Pipe or infiltration chambers are not needed for short trenches or when a trench is constructed parallel to the surface from which it is harvesting runoff, such as along the edge of a patio. Perforated pipe or chambers are used to distribute water more evenly within trenches exceeding 20 feet (6 m) in length.

Caution: I typically construct infiltration trenches without pipe to reduce the expense and environmental impact of plastic pipe, and because roots can enter and clog pipe over time. However, there are strategies that can lessen root intrusion into pipe, such as wrapping an infiltration trench with landscape fabric, or better yet, using infiltration chambers instead of perforated pipe.

Note 1: Gravel-, pumice-, or mulch-filled *infiltration trenches hold only about one-third to one-half as much water as open berm 'n basins or infiltration basins hold*. However, the water harvested in an infiltration trench is less prone to evaporation due to the fill material.

Note 2: Unlike infiltration basins, infiltration trenches are out of sight, so most people will not know they exist nor understand their benefits, and problems will be harder to find and fix.

WHERE IS AN INFILTRATION TRENCH USED?

Infiltration trenches are used on gently sloped or flat land where you want the water-harvesting potential of a berm 'n basin or infiltration basin, but not the obstacle that a berm or open basin might create. For example, they are suitable adjacent to paved parking areas, driveways, or patios. Placed there, they immediately intercept the runoff from the paved surfaces, while giving folks more room to safely run or walk around cars, patio furniture, or other people (fig. 5.1). Do not place an infiltration trench across a driveway used by cars, as their weight could sink them into water-saturated soil.

Place an infiltration trench only where it will intercept relatively sediment-free water, such as at the end of a rain gutter's downspout pipe or at the edge of a paved surface. Do not use infiltration trenches to capture runoff from dirt catchment surfaces or within natural drainages where they would quickly fill up with the sediment carried by the runoff. Once this sedimentation happens most of the original water-holding capacity of an infiltration trench is lost.

Infiltration trenches with pipe are used extensively to capture water falling from canale roof drains of Santa Fe-style homes. The drain gets the water away from the foundation of the house and into the landscape where it can passively irrigate plants (fig. 5.3).

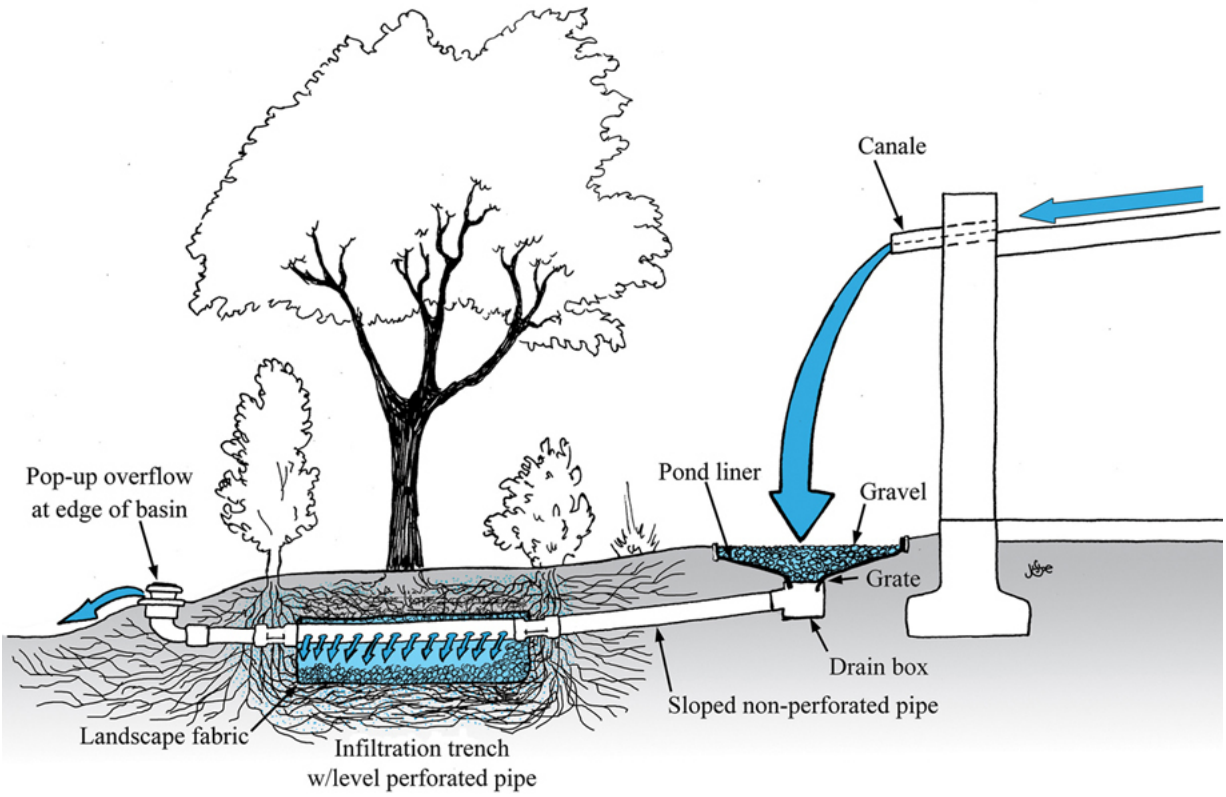


Fig. 5.3. A canale roof drain, drain box, and pipe directing roof runoff away from the house to an infiltration trench within the landscape. Note: While the illustration's perspective may be misleading, the vegetation is planted adjacent to the infiltration trench, not on top of it. See fig. 5.11 for the option of using infiltration chambers instead of perforated pipe and gravel.

TOOLS AND MATERIALS

Basic tools: a pointed shovel, flat shovel, pick or digging bar, and level (see appendix 1 which describes simple tools for measuring slope).

Helpful machinery: Ditch Witch or backhoe.

Materials include porous fill such as inorganic open-graded, angular gravel or aggregate (fig. 5.6B); pumice; escoria; rocks; or organic compost, straw, cut-up prunings, woodchips, or bark. Fine organic matter is more likely to wick and/or maintain a little more moisture higher in the profile of the infiltration trench, whereas large, course inorganic aggregate is more likely to send more water to the bottom of the trench. Pumice and basalt enable you to hold more water than other gravel due to their more porous nature. (Use basalt rather than pumice if the drain will be regularly walked on or if you live in a cold

climate, since pumice is softer and breaks down more readily from disturbance and freeze-thaw cycles). Small or large prunings can be placed in the bottoms of infiltration trenches before covering them with gravel. Turn such nontoxic "wastes" into resources.

If you use perforated pipe within your trenches, wrap landscape fabric around the fill material to help keep roots from growing into the pipe (5.9B). Use non-perforated rigid plastic pipe to move water from one point to another. Use perforated 4-inch-diameter (100-mm-diameter) rigid pipe in the length of the trench where you want infiltration to occur. Rigid pipe is less likely to sag than flex pipe, reducing clogs from accumulated debris and distributing water more evenly.

Infiltration chambers (no taller than 13 inches or 33 cm) from InfiltratorSystems.com or Hancor.com can be used instead of perforated pipe, and landscape fabric is not needed since roots are far less likely to grow into the large air space within the chambers.

STEPS TO BUILD AN INFILTRATION TRENCH

SITING

I typically limit infiltration trenches to areas of heavy foot traffic where I want to harvest runoff from relatively sediment-free surfaces without creating a tripping hazard.

Site the infiltration trench where you want to increase infiltration of water into the soil in the root zone of plants, which grow adjacent to, but not in, or on top of, the infiltration trench. Do not place infiltration trenches where you don't want plants or their roots to grow, such as across or beneath roads, driveways, or paths. If placing an infiltration trench on a gradual slope, try to lay it on contour. An A-frame or bunyip water level, or transit will help you get it right.

To prevent infiltration trenches from prematurely silting up, place berm 'n basins, sheet flow spreaders (chapter 10), or infiltration basins upslope of infiltration trenches in the unpaved sections of landscapes that would otherwise shed sediment-laden runoff into the infiltration trench (fig. 5.4).

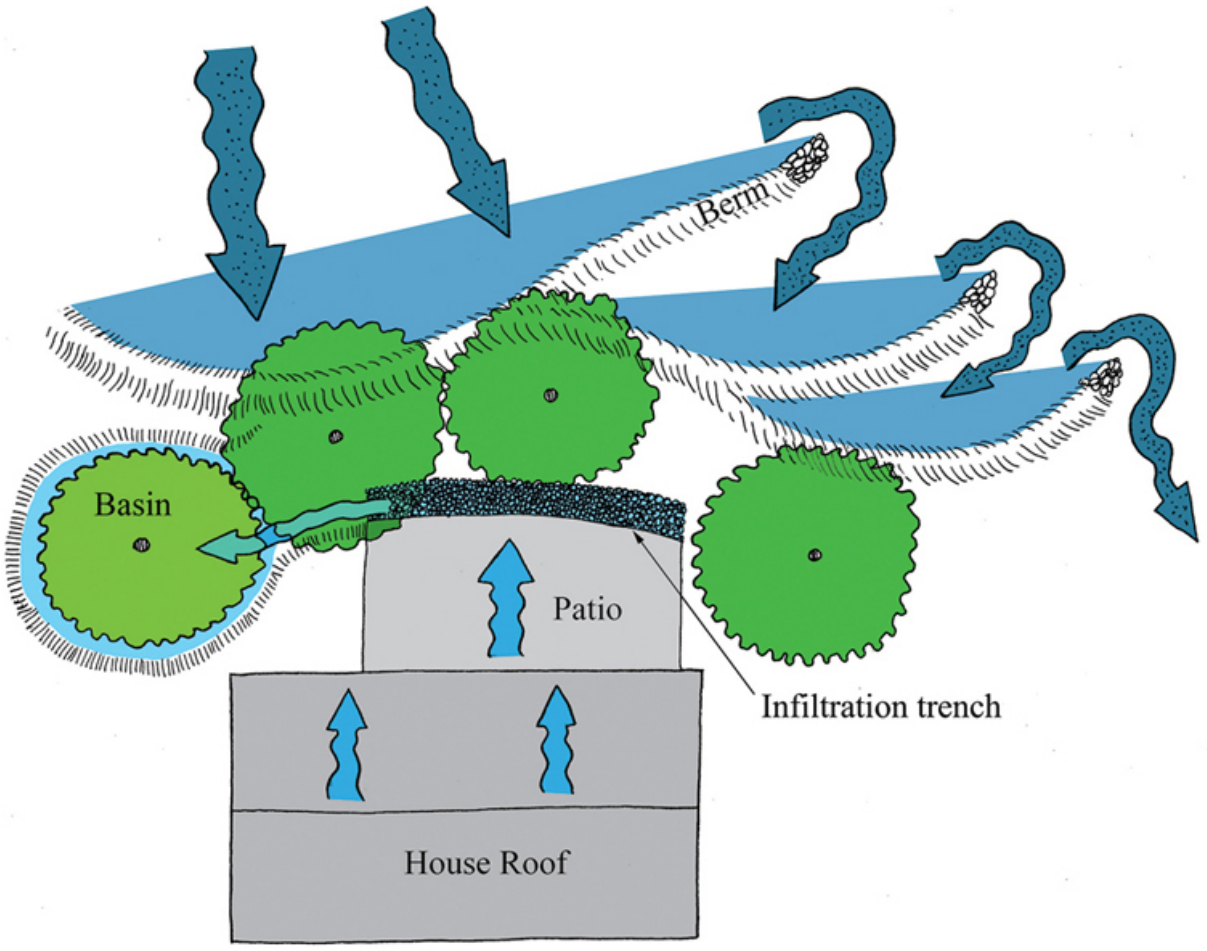


Fig. 5.4. Berm 'n basins placed upslope of an infiltration trench intercept and infiltrate sediment-laden runoff with overflow directed to other berms and away from the infiltration trench. The infiltration trench intercepts sediment-free runoff from roof and patio with overflow directed to a tree within an infiltration basin.

SPACING

A pipeless infiltration trench should be placed close to the paved surface from which it is harvesting runoff. A stabilizing flat curb or spillway placed between pavement and trench will prevent the pavement from being undercut by water flowing into the infiltration trench. (See fig. 5.5.)

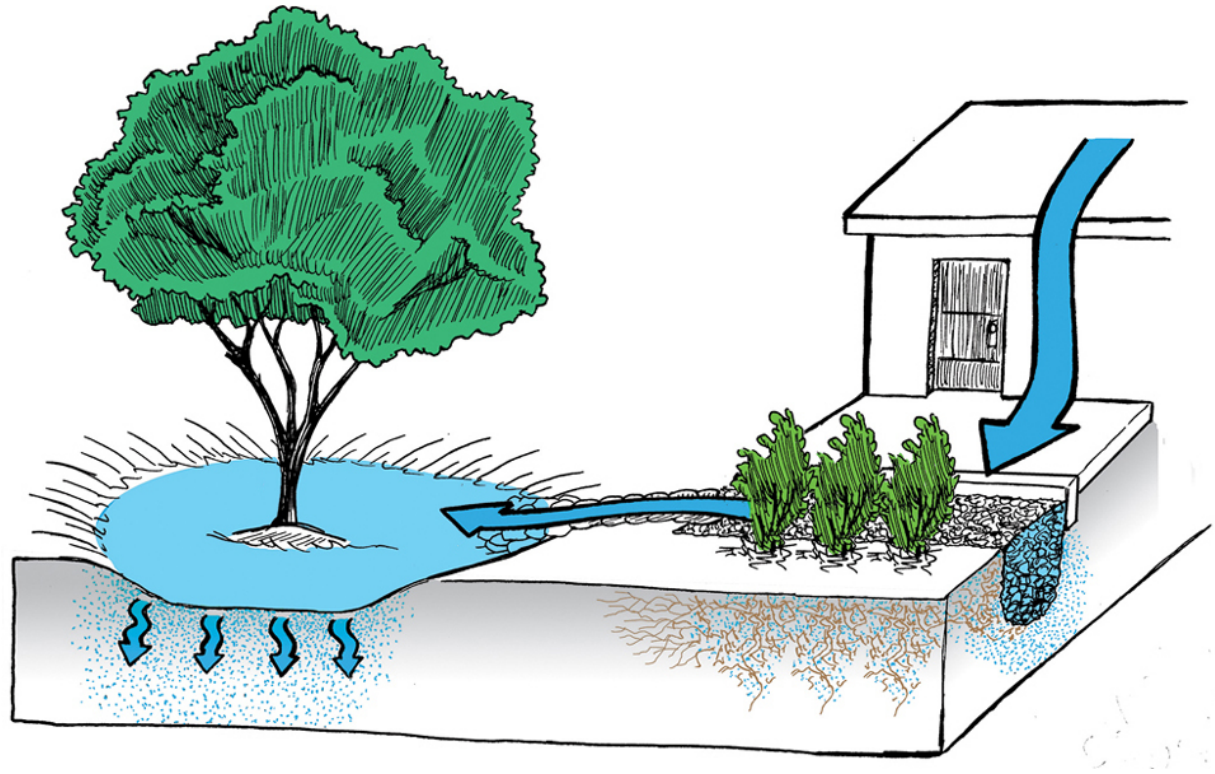


Fig. 5.5. Infiltration trench without pipe; overflow directed to an infiltration basin. Notice the stabilizing flat curb between the patio and infiltration trench.

Infiltration trenches can be placed farther away from their water source if non-perforated pipe transports the water to the trench.

As with all water-harvesting earthworks, an infiltration trench should be at least 10 feet (3 m) from the foundation of any building.

APPROPRIATE SIZE

Use the catchment calculations found in appendix 2 to estimate how much water you expect to flow into your infiltration trench at one time. Remember, the presence of porous fill material will reduce the water-holding capacity to about one-third to one-half of the trench's total volume. Either make your infiltration trench large enough to take all the expected flow or plan to route the extra flow to other earthworks.

Make your infiltration trench a minimum of 15 inches (38 cm) wide and 15 inches deep. My experience is that anything shallower or narrower collects too little water to justify the work. The length will vary depending on the water-

holding capacity you need, where runoff originates, and where you want the runoff to support plants.

CONSTRUCTION

To attain maximum water infiltration, dig a hole or trench with near-vertical sides on contour, but you don't have to make a berm. The soil dug from the trench can be used to raise the level of a nearby pathway or patio so that it will shed water to adjoining infiltration trenches or basins. If you do make a berm, place it on the downslope side of the infiltration trench. Make the bottom of your basin or trench level to encourage even infiltration of water.

Rake and rough up the bottom and sides of your trench if they were compacted or smeared smooth during excavation to improve the permeability of the soil lining your trench. Also, remove large stones or other debris from the bottom of the trench. Verify that the trench is still level.

The next sections describe, first, an infiltration trench without pipe, and then, an infiltration trench with pipe.

Infiltration trench *without* pipe

After digging your trench, and, if desired, placing cardboard at its bottom (see box 5.1), fill it with gravel, stones, coarse organic mulch, or other appropriate material that leaves large pores for water to move quickly through and infiltrate into the adjoining soil.

Box 5.1. Using Cardboard to Encourage More Lateral Infiltration of Harvested Water into the Root Zone of Plants

Water-harvesting systems designer Richard Jennings of Earthwrights Designs puts a layer of cardboard on the bottom of his infiltration trenches to create a less permeable bio-mat of decomposing material, which pushes more of the water infiltration to the sides of the trench. This keeps more of the water in the top 2 feet (0.6 m) of the soil, and the densest root zone of adjacent plants. Old magazines or layers of newspaper could also be used.

To be porous, permeable, and stable under a load, aggregate or gravel particles must be angular in shape so their flat faces interlock with each other and resist rotating and shifting. "Crushed stone" or "crushed gravel" are appropriately angular materials, as opposed to smooth round "river stone" or

"pea gravel," which rotate and slip past each other and "give" under a load (fig. 5.6A). The aggregate must also be open-graded or single-sized, which results in the aggregate having a narrow range of particle sizes and open void spaces that improve interlocking between particles (fig. 5.6B).

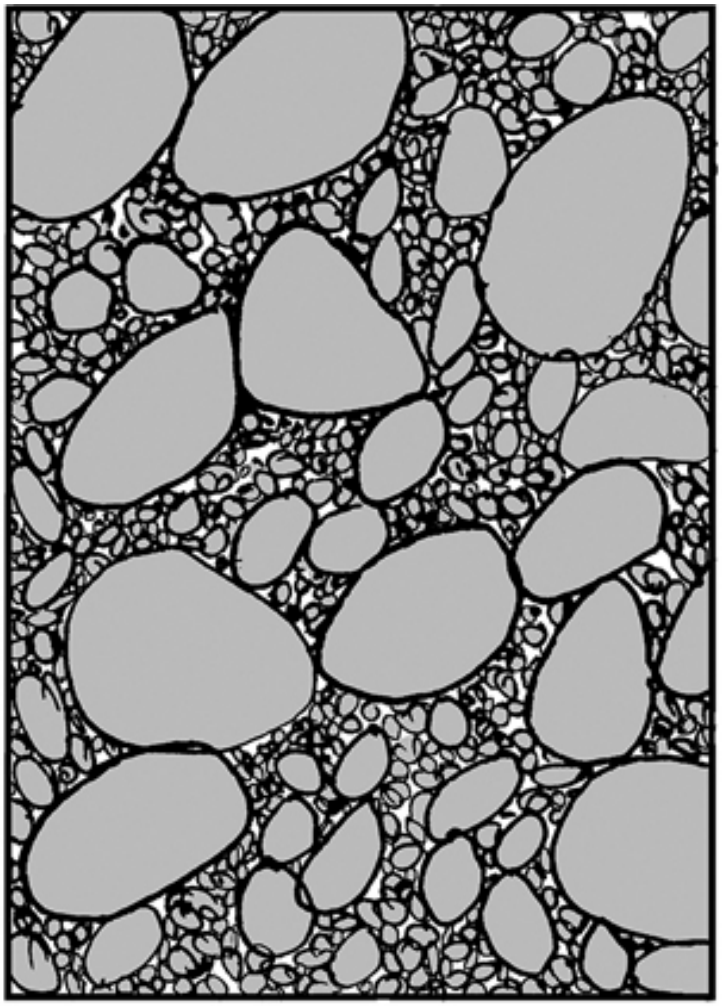


Fig. 5.6A. Round mixed-size inorganic (gravel) particles packed in dense gradations results in *low* water capacity

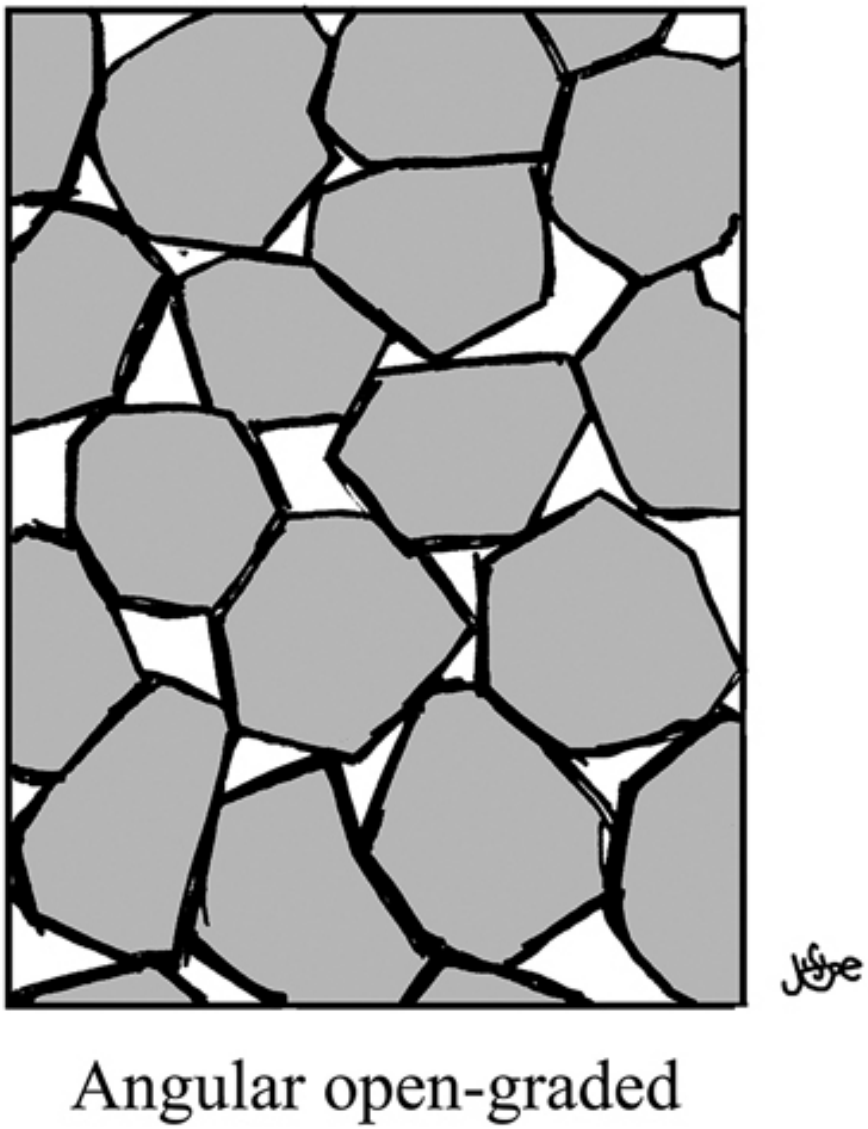


Fig. 5.6B. Angular single-sized inorganic (gravel) particles packed in open-graded gradation results in *higher* water capacity.

Make sure the open-graded gravel you select is durable enough not to wear down to finer material. Before delivery have it washed clean of fine particles that could clog the pores between the aggregate. While aggregate with particle sizes up to 1 inch (2.5 cm) drain rapidly, 1/2-inch (1.25-cm) particles are easier to walk on. If filling with pumice or basalt/volcanic stone, use 5/8-inch (1.5-cm) diameter or larger so your infiltration trench won't plug with smaller

pieces of the pumice, called "fines." Tamp the upper layer of gravel by stomping on it with your feet or tamping it with a hand tamper to get the gravel to better interlock with itself and stay put.

Avoid gravel fill in trenches in garden settings, because the gravel is horrible to dig into or till. Instead use coarse, dig-friendly, organic mulch. Organic matter such as straw bales, loose straw, and good-sized chunks of bark work well as fill, but these materials will need to be replenished as they break down. This decomposition creates great soil but as it decomposes the air spaces become smaller and water infiltration is reduced. Nevertheless, infiltration rates will still be better than they were before making the infiltration trench.

OVERFLOW**:** Since the top of a pipeless infiltration trench is typically "at grade" (level with the surrounding soil), excess runoff that fills the drain will overflow and continue along its original path. One way to direct overflow to other water-harvesting earthworks is to construct the lowest point of the rim of the infiltration trench in the direction where you want the water to overflow. Then use a diversion swale to direct the water to a specific location. (See chapter 9 on diversion swales).

Infiltration trench *with* pipe

HARVESTING WATER FROM A CANALE: Create a funnel drain to capture the water falling from the canale by digging a 3- to 4-foot (90–120 cm)-diameter hole beneath the end of the canale (refer to fig. 5.3).

Place a 12-inch (30-cm) plastic drain box in the center of the hole, with the drain box's outflow hole facing toward your future infiltration trench. The top of your drain box should be about 6 inches (15 cm) below grade with the grate facing up. Then, dig a trench for, and install, non-perforated 4-inch (100 mm)-diameter plastic pipe from the drain box to the area of the landscape where you want to infiltrate the water (should be a minimum 10 feet from building foundation). The non-perforated pipe must drop at least 1/4 inch per horizontal foot (2 cm drop per horizontal meter).

Now go back to the drain box to finish making your funnel. Backfill around the drain box with soil up to the top of the box, then add more backfill creating a gradual slope from grade to drain box grate. Remove the grate atop the drain box. Place a 4- to 5-foot (120–150 cm)-wide piece of 20- to 40-mil

plastic pond liner over the drain box (pond liner is available from building, pond, and plumbing supply stores, and while less expensive shower liner can be used in warmer climates, it often disintegrates in cold ones). Cut the center of the plastic with two cuts in the shape of an X—make sure these cuts are less than the width of your drain box so all water will be directed into the box (fig. 5.7A). Put the grate back on the drain box over the hole you cut in the plastic to hold everything in place. Then cover the drain box with rock or gravel larger than the hole size of the grate so you don't fill the box with rock. Install a ring of large rock or steel edging around the border of your drain box's funnel to further reduce sediment from entering the drain and make a neater appearance (fig. 5.7B).

5.7A. Pond liner and drain box with the X-cut in the pond liner beneath the grate so water can freely drain into the drain box. Canale (not pictured) drain roof runoff to drain boxes on either side of the home's corner. Installation and photo by Raincatcher Incorporated, Santa Fe, New Mexico

5.7B. Drain boxes and pond liner covered with rock (though gravel could be similarly used) larger than the drain box grate. Rock is rung with steel edging to keep rock in place and sediment out. Installation by Raincatcher Incorporated, Santa Fe, New Mexico

Now go back to the end of your non-perforated pipe to connect and lay the perforated pipe.

HARVESTING WATER FROM A DOWNSPOUT PIPE: Connect non-perforated plastic pipe to the base of your downspout. The pipe diameter must not be less than the downspout's diameter; 3 inch (75 mm) to 4 inch (100 mm) is typical. Dig a trench and run the pipe to the area of the landscape where you want to infiltrate the water (should be at least 10 feet [3 m] from the building foundation). Slope the pipe run so there is at least a 1/8th-inch drop for every foot of horizontal (1-cm drop per meter of horizontal length). Then connect the non-perforated pipe to the perforated pipe (fig. 5.8).

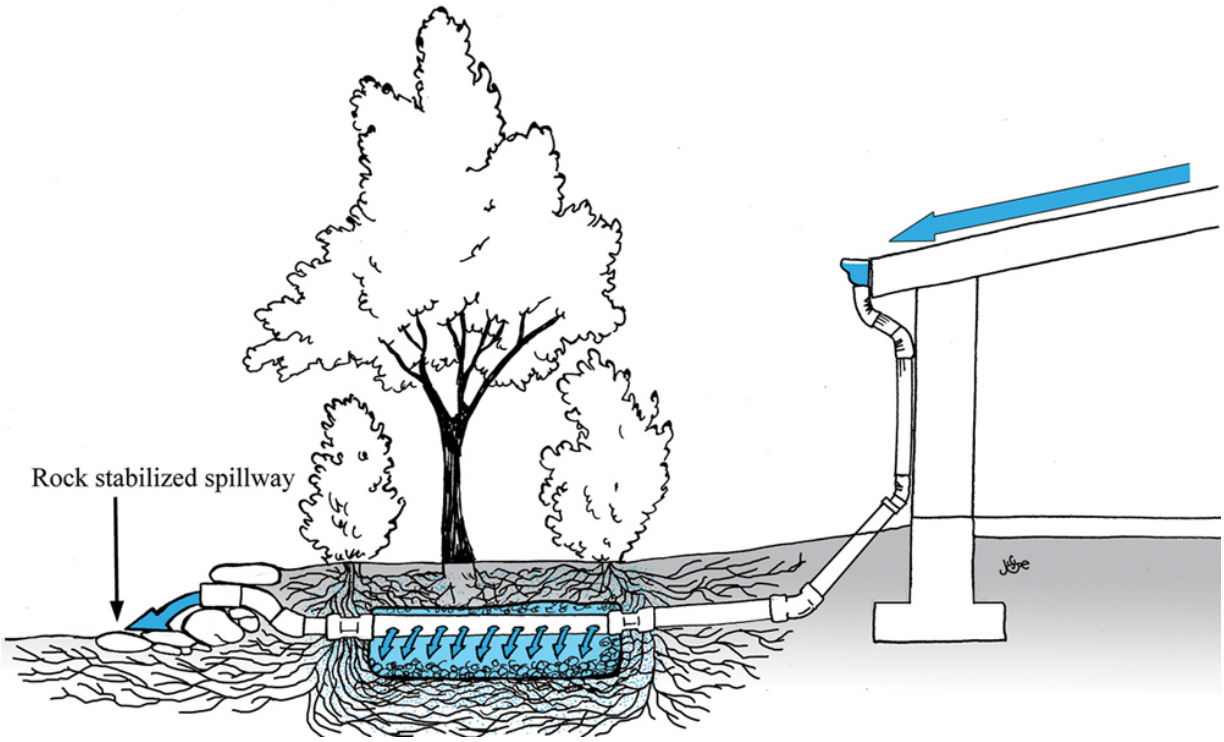


Fig. 5.8. Infiltration trench with pipe connected to downspout. Note the overflow (exiting a dry-laid retaining wall) is higher than the perforated pipe in the infiltration trench, so most of the water infiltrates into the drain, while the overflow is lower than the inflow elevation where the downspout enters the pipe, so no water backs up against the house. A rock apron diffuses the falling overflow water. Note: The vegetation is planted adjacent to the infiltration trench, not on top of it. Compare to fig. 5.3 which shows overflow from a canale.

LAYING PERFORATED PIPE: Perforated drain pipe should be installed *level* within a level trench about 15 inches (38 cm) wide and 15 inches deep. You want to infiltrate the water into the root zone of plants, so avoid trenches deeper than 24 inches (61 cm)—15 inches (38 cm) is better.

Line the trench with landscape fabric if you want to deter root growth into the infiltration trench. Fill the bottom of the trench with 8 inches (20 cm) of pumice or gravel and tamp it with your feet or a hand tamper. Connect your perforated pipe to the non-perforated pipe from the canale or downspout. Lay the rigid perforated pipe level on top of the gravel, aiming the pipe holes to the sides of the trench. This allows a 1/2 inch (1.25 cm) of water to fill the entire length of pipe before it spills out all the holes—more evenly distributing the water. (See figs. 5.9A and 5.9B).

Fig. 5.9A. Perforated pipe being laid level within an infiltration trench of scoria gravel wrapped in landscape fabric. The infiltration trench will direct roof runoff to passively irrigate a line of trees on left. Credit: Raincatcher Incorporated

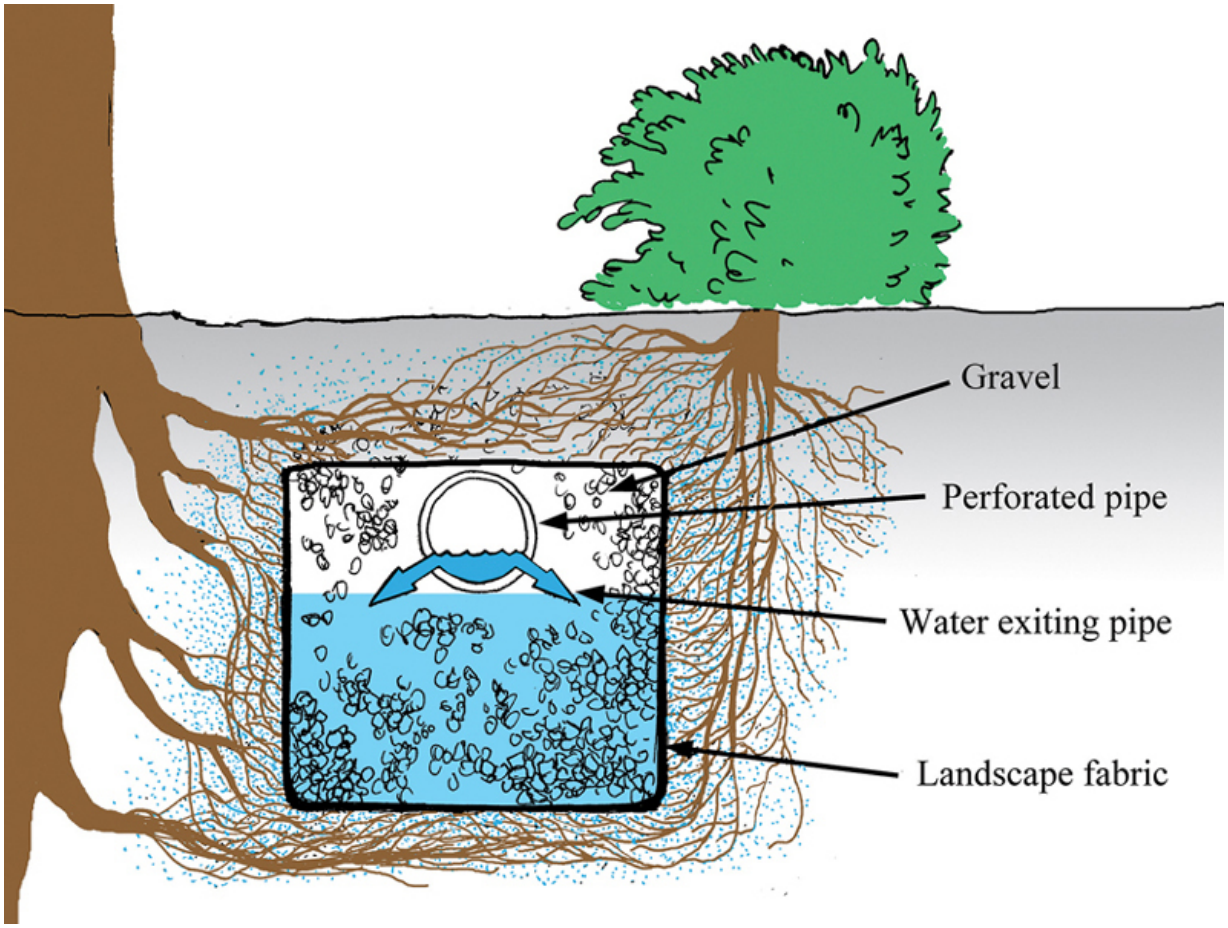


Fig. 5.9B. Cut-away view, looking into perforated pipe within an infiltration trench

OVERFLOW: Install an overflow outlet at the end of your pipe run. This could be a pop-up overflow (see fig. 5.3) allowing surplus water to surface at an elevation below the downspout inlet, or an opening releasing surplus water through a terrace wall or into an infiltration basin (fig. 5.8). Either way, make sure your overflow outlet is above the perforated pipe so most of the water will infiltrate the infiltration trench, and below the drain box or downspout inlet so no water will back up against your house. Direct overflow water to another water-harvesting earthwork, a natural drainage, or (if no other option) a stormwater drain.

COVER UP: Once all pipe is laid within the trench, check to make sure the perforated pipe is level and all solid pipe slopes at least 1/2 inch per 10 linear feet (1.25 cm per 3 m). Then cover the pipe with more pumice or gravel. To prevent dirt from prematurely silting up the drain, either wrap the top of the gravel-filled trench with landscape fabric or place 20 to 24 sheets of newspaper atop the gravel. Cover the landscape fabric or newspaper with 2 to 10 inches (5–25 cm) of soil and tamp it in place.

Infiltration trench with infiltration chambers

For water-harvesting infiltration trenches with "pipe," I prefer using bottomless, louvered-sided infiltration chambers instead of perforated pipe (box 5.2). Because the chambers have such a large air space within them, roots rarely grow into and clog the chamber as they typically do with smaller-interior perforated pipe. Instead, roots grow to form a beneficial root mat under the chamber, but they are not likely to grow into and clog the chamber (see fig. 12.16 in chapter 12 for an interior view of a chamber used in a greywater-harvesting application). In addition, the chambers provide for a greater water-holding and water-distribution capacity due to their larger interior void space, which does not plug with sediment as can eventually happen with gravel- or crushed-stone-filled trenches. Thus, no landscape fabric is needed, and native soil can be used rather than gravel to backfill around the chambers, allowing you to plant or seed directly beside the chamber. Don't plant trees or large shrubs directly on top of the chambers because they will collapse the chambers with their weight, and you want to retain access to the chambers should you ever need to dig them up.

Box 5.2. Cautions

1. In some instances the installation of infiltration trenches may require permits from the U.S. Environmental Protection Agency (EPA). According to the EPA, infiltration trenches could be considered Class V stormwater drainage wells if they are lined with drain tile or installed with piping for subsurface distribution of fluids. Such wells are regulated by EPA and by primacy states (states that have primary enforcement responsibility for their Public Water System Supervision programs). Regulations through the Underground Injection Control (UIC) program protect underground sources of drinking water (USDWs), from runoff that enters stormwater drainage wells, which may be contaminated with sediments, nutrients, metals, salts, fertilizers, pesticides, and microorganisms. A USDW is defined as an aquifer that contains less than 10,000

mg/liter total dissolved solids and is capable of supplying water to a public drinking water system.[1]

Infiltration trenches are not considered storm-water drainage wells if they are excavated trenches filled with stone or coarse organic matter and do not include piping or drain tile. In such instances, they are usually wider than they are deep.

2. Infiltration trenches collecting runoff from a potentially polluted surface such as a parking lot or driveway may carry pollutants along with the infiltrating water into the soil. As a result, infiltration trenches and other underground infiltration structures may require a Discharge Permit from your state environment department. Check with officials in your area to determine if a permit is needed.

Infiltration chambers were originally designed for septic leach fields, though they work great for water-harvesting infiltration trenches and greywaterharvesting systems too. They can be purchased from septic system suppliers, and are manufactured by Infiltrator Systems Inc. (InfiltratorSystems.com) and Hancor (Hancor.com). Both companies provide detailed installation instructions. And for installations within trenches curving along contour lines, Infiltrator Systems offers angled connection joints called "contour swivel connections" that link up their "Quick4" chambers in a curvilinear pattern. Hancor offers a similar system.

5.10A. *Before* infiltration trench installation. Yellow caution tape marks where the infiltration trench will go. Photo by Charles Mann, courtesy of PermaDesign, Santa Fe, New Mexico

5.10B. *After* infiltration trench installation. Design, installation, and photo by PermaDesign, Santa Fe, New Mexico

Whether your trenches are straight or gradually curved, place the chambers atop the level bottom of your trench, connect as many chambers as needed to attain the desired capacity of your system, and cap the two ends with end caps. Incoming non-perforated pipe is connected to one end, and a non-perforated overflow pipe is connected to the other end. Add an inspection port or two, and cover the chamber(s) with native soil dug from your trench (see fig. 5.11). You will likely want to cover the chamber(s) with a slight mound of soil at first, because the soil will settle as it recompacts into place.

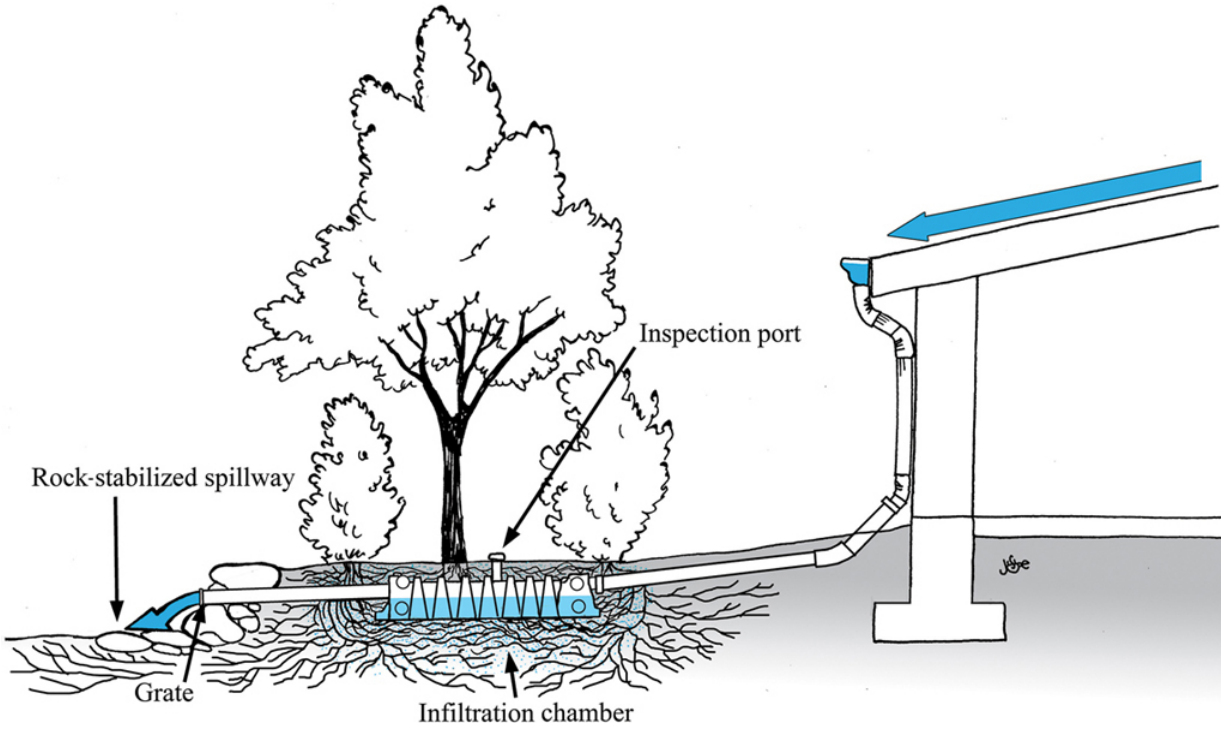


Fig. 5.11. Infiltration trench with infiltration chamber—my preferred system with pipe. Non-perforated pipe brings the water to the chamber and takes surplus away via the overflow pipe. The large void space in the bottomless, louvered-sided chamber is unlikely to clog with roots so no landscape fabric is needed, and the chamber can be covered with native soil rather than gravel. The chamber could also be used instead of perforated pipe and gravel with a canale installation (fig. 5.3).

Be sure you obtain chambers that do not exceed 13 inches (33 cm) in height. This way you can dig a shallower trench and more easily distribute the incoming water into the top 2 feet (0.6 m) of the soil where the bulk of the soil life and roots will utilize the water. The Infiltrator Systems' "Quick4 Standard Chamber" or "Low Profile Standard Chamber" or Hancor's "EnviroChamber ProArc Standard Chamber" are ideal.

PLANTING YOUR INFILTRATION TRENCH

Plant around, rather than in, an infiltration trench. Perennial plants are best (see chapter 11 on vegetation). Vegetation prolongs the life of infiltration trenches by stabilizing soil and acting as a living filter that catches sediment before it reaches the drain. Native grasses and indigenous groundcovers work well. They can be planted beneath sheltering trees that use the water harvested

in the drain. If leaf drop is allowed to accumulate and the plants are allowed to grow, the soil underneath will be loose, porous, and fertile with organic matter, creating a natural sponge for rainwater infiltration. Infiltration trenches might eventually silt up, but the vegetation and healthier soil they help establish create a "living infiltration trench."

MAINTENANCE

Check your infiltration trenches periodically, especially during or following big rains, and make repairs or adjustments as needed. Add fill material after the original fill has settled.

VARIATIONS OF AN INFILTRATION TRENCH

DEEP-PIPE IRRIGATION

David Bainbridge, author of the books *Gardening With Less Water* and *A Guide for Desert and Dryland Restoration*, developed deep-pipe irrigation to direct irrigation water deep into the root zone of associated plantings. He accomplishes this deep irrigation by inserting a plastic pipe or bamboo tube vertically into the soil. Deep-pipe irrigation encourages deep root growth, producing more drought-tolerant plants than surface irrigation produces. In addition, less irrigation water is lost to evaporation and there is less weed growth (fig. 5.12A).

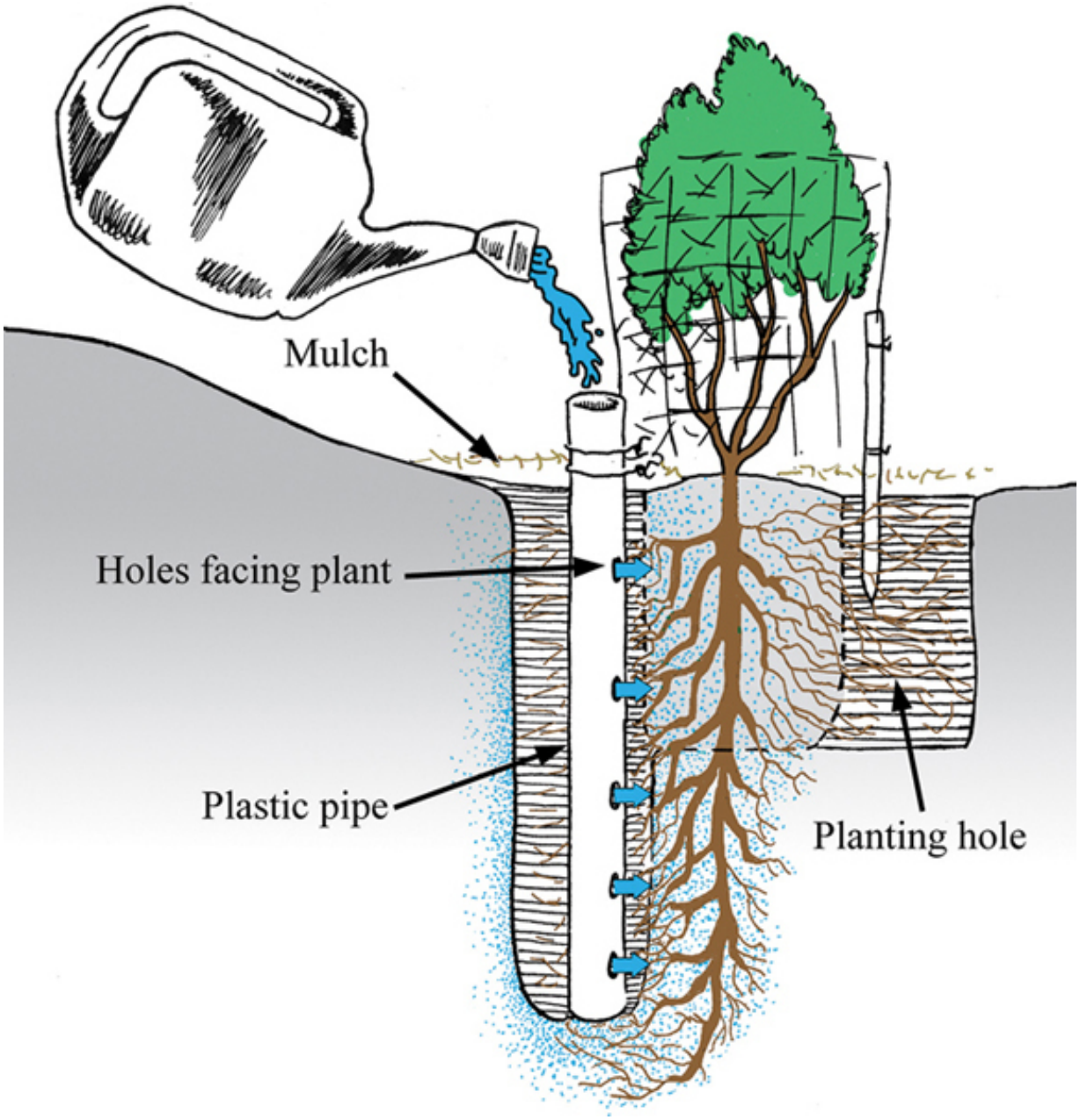


Fig. 5.12A. Deep-pipe irrigation within an infiltration basin. See fig 2.25 for another option

Using 3/4- to 2-inch (19- to 50-mm)-diameter plastic pipe for drip-irrigation emitters or hand watering, and 4-inch (100-mm)-diameter pipe for water-truck watering, cut the pipe in 18- to 24-inch (45–60 cm)-long sections. Starting 6 inches (15 cm) down from one end of each pipe section, cut or drill holes on one side of the pipe at 3-inch (7-cm) intervals.

Dig a hole within a water-harvesting earthwork that is large enough to hold a perennial plant and the pipe. Place the plant against one side of the hole; then set the pipe vertically against the plant's root ball. The holes or slits in the pipe should be facing the plant. Leave 3 to 6 inches (8 to 15 cm) of pipe sticking up above grade so sediment does not flow into and clog the voids between the gravel. Backfill around the plant and pipe, then mulch the surface of the soil. Fill the pipe with 1/2-inch (1.25-cm)-diameter gravel or rock. If installing drip irrigation place an emitter in the end of the pipe. If you need fencing to keep critters from nibbling on your plant, you can use the end of the pipe as a stake to hold the fencing in place. After plant establishment, the pipes can be pulled and reused.

ROCK-TUBE IRRIGATION

Rock-tube irrigation uses a gravel-filled tube of landscape fabric instead of pipe to accomplish deep irrigation. The porous fabric filters out sediment, while allowing harvested runoff and irrigation water to seep into the tube and quickly infiltrate deep into the soil (fig. 5.12B).

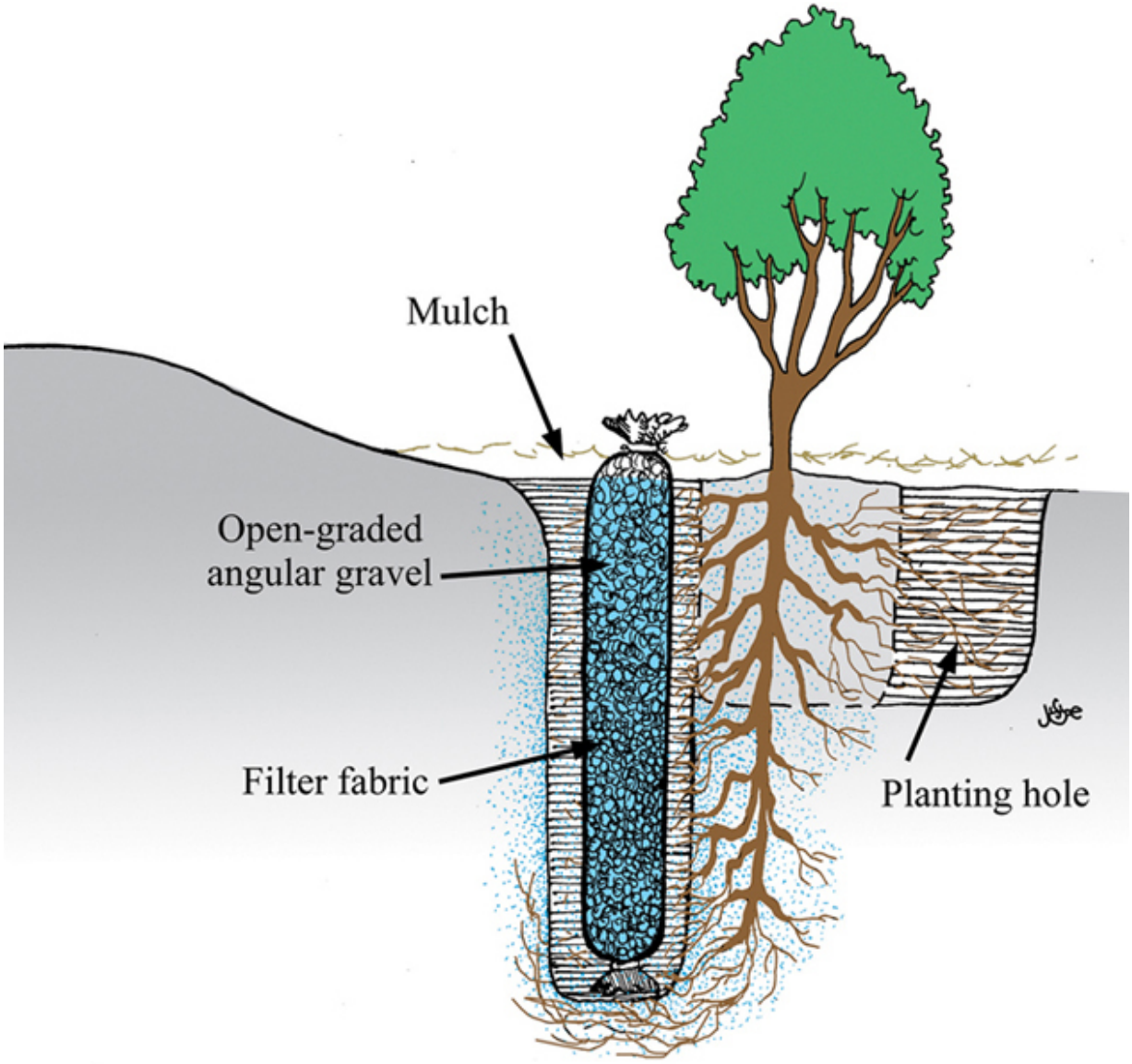


Fig. 5.12B. Rock-tube irrigation within an infiltration basin. See fig 7.10 for another option

The San Isidro Permaculture crew of Santa Fe describes the construction process as follows: Cut a piece of 4-inch (100-mm) diameter plastic pipe that is 6 to 12 inches (15–30 cm) longer than the depth of the root ball of the plant you are planting. Wrap the pipe with landscape fabric, overlapping the fabric 6 inches (15 cm), and pinning it together with long nails, wire, or landscape pins. Tie off the bottom end like a sausage. Dig a hole for your plant and tube as you would for a deep-irrigation pipe. Tubes are typically planted 6 to 12 inches (15-30 cm) deeper than the plant's rootball to encourage roots to grow

down deep. The top of the tube is at or just above grade. Set the plant and tube in place, then backfill around them both. Fill the pipe within the tube with 1/2-inch (1.25-cm) or larger-diameter gravel, then pull out the pipe to use on another rock tube. Tie off the top of the tube and cut off any excess fabric. Mulch the surface of the basin around your plant and tube.

For a similar strategy using only mulch (no pipe or landscape fabric) see the vertical mulch variation in chapter 7.

STRUCTURAL SOILS AND SOIL CELLS

In the high-density urban environment, unpaved and uncompacted soil is rare. The compaction of urban soils by heavy machinery during paving construction and by the weight of overlying pavement can crush soil macropores and make soil extremely dense, inhibiting water infiltration and root growth. Trees planted within these highly paved and compacted soils are less healthy due to limited root growth, and fail to reach their natural mature canopy size. Roots may grow abnormally close to the surface, heave pavement, and be too shallow and hemmed in to keep trees upright in high winds. However, a combination of structural soils or soil cells and correct tree selection, in what's often called a "tree trench" or "stormwater tree trench," can result in healthy trees with enhanced root growth that do not heave pavement or topple over in storms.

Structural soil is often used in the very urban environment to provide structural support to the paved surface above while creating a 'soil' environment below the pavement that has sufficient void space and nutrients to enhance root growth (fig. 5.13). The components of structural soil are 1) uniformly sized, highly angular crushed stone ranging from 0.75 to 1.5 inches (19 to 38 mm) in diameter with no fine materials; 2) clay loam having an organic matter content ranging from 2 to 5%; and 3) a hydrogel stabilizing agent to keep the mixture from separating during mixing, transit, and installation.[2]

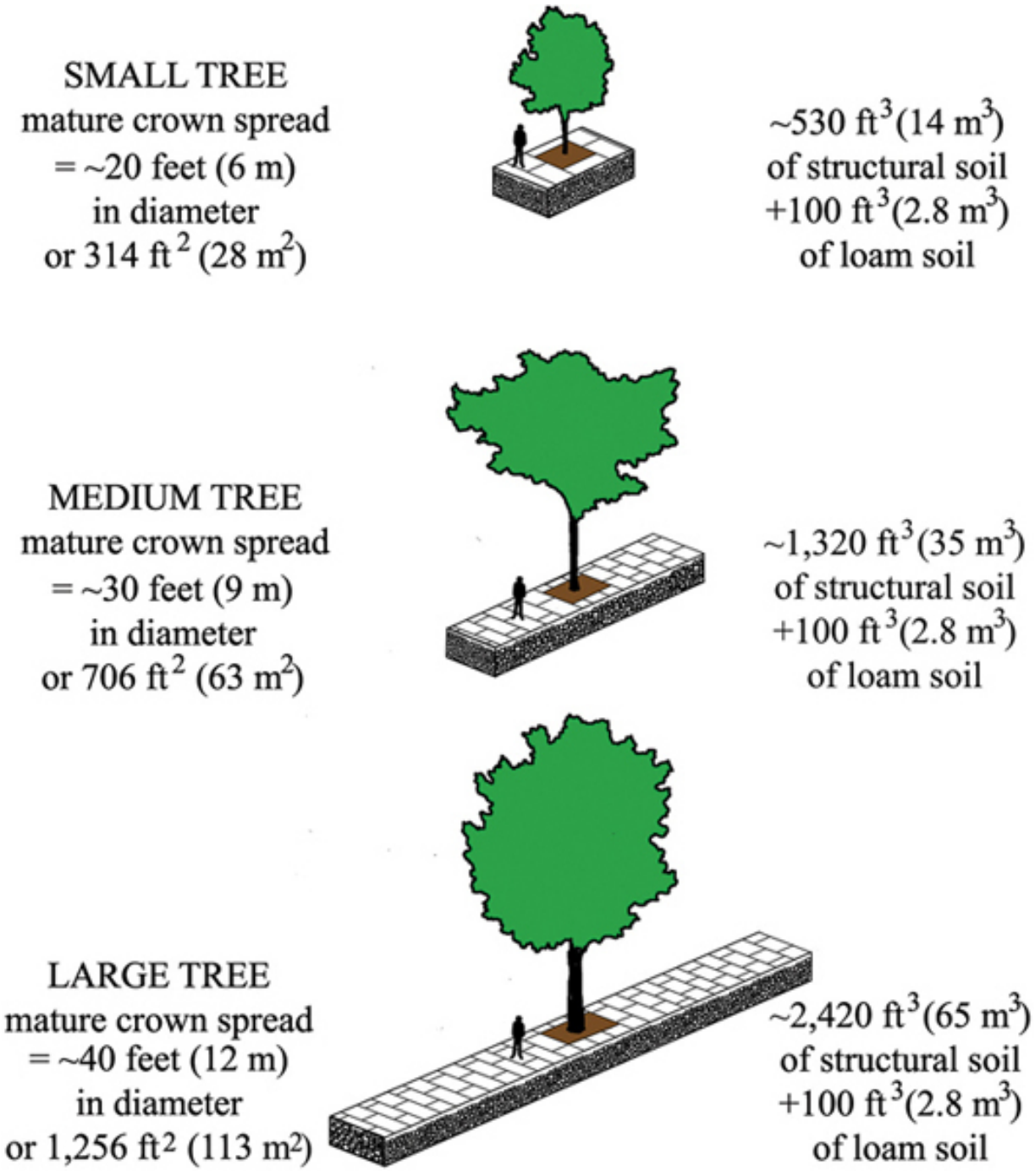


Fig. 5.13. Structural soil volumes needed to support various tree sizes, in addition to the 100 ft^3 (2.8 m^3) of loam soil the root ball is planted in. The structural soil used is a 3-foot (1-m) deep base material over which porous pavement is installed. Adapted from *CU-Structural Soil: A Comprehensive Guide* by Nina Bassuk, Bryan R. Denig, Ted Haffner, Jason Grabosky, and Peter Trowbridge. Such an application is sometimes referred to as a "tree trench."

The crushed stone provides a skeleton structure that interlocks when compacted to support the pavement laid upon it. The void spaces between the crushed stone allow water, air, and roots to freely flow and grow through it. The clay loam is added to provide moisture- and nutrient-holding capacity.[3] There are different structural soil mixes, both proprietary and non-proprietary. One mix uses a ratio of 80% stone, 20% clay loam, and a small amount of hydrogel or tackifier to reduce the likelihood of the mix separating. However, this ratio of structural soil cannot be transported far because the clay can separate from the gravel during transport.[4] Other mixes for different installation strategies may not use a tackifier. Whatever the mix, avoid the use of any liners below the structural soil because you want tree roots to be able to access the underlying subsoils.

Plan for at least two cubic feet of structural soil for every square foot of the projected mature diameter of the tree's crown.[5] In metric units, plan for at least 0.6 cubic meters of structural soil for every square meter of the projected mature diameter of the tree's crown. However, in hot, arid climates the rule of thumb for the needed volume of structural soil should be increased.[6] The minimum depth of structural soil should be 2 feet, but 3 feet is preferable to allow roots to grow away from the fluctuating temperatures of the pavement's surface.[7]

In the simplest installation, porous pavement (see chapter 8) is placed over the structural soil containing the tree's root zone to allow for the harvest of rainfall into the root zone (fig 5.13). Because there is little to no stormwater runon harvested, no underdrain for overflow water is necessary.

In a more complex installation, the structural soil is designed to intentionally harvest stormwater runon from adjacent catchment surfaces, so stormwater inlets with sediment/debris filters may be added. Such installations typically include an underdrain system for overflow water—especially when installed over poorly draining clayey soils (typically C and D soils). Underdrain systems significantly increase infrastructure, costs, and maintenance and limit where structural soil systems can be constructed. However when structural soils are installed over well-drained sandy soils (typically A and B soils) no underdrain system is needed.[8]

A related strategy uses a framework of modular plastic cells, or *structural soil cells*, rather than crushed stone/gravel to support the pavement above (fig. 5.14). These create a void space for water and uncompacted soil below the pavement and within the cells. Structural soil cells provide more nutrient-rich soil per unit volume than structural soil, since no crushed stone/gravel is taking up valuable space below the pavement.[9] To learn more, search online for Silva Cells and StrataVault along with other suppliers of structural soil cells.

Fig. 5.14. Silva cell soil cells used beneath porous pavement to harvest rainfall and enable extensive root growth and healthy urban trees. Sugar Beach, Toronto, Canada. Reproduced with permission from DeepRoot Green Infrastructure

In terms of cost, average structural soil costs are 30 to 45% less than the cost of soil cell systems of the same size. However, for the structural soil to provide the same amount of uncompacted soil volume for tree roots to grow in as soil cells, up to five times the volume of structural soil is required.[10] Note that

structural soil works better than uniformly sized soil cells if subsurface areas are non-uniform and/or constrained by utilities.[11]

According to the report *Application of Stormwater Tree Trenches in the City of Vancouver*,[12] trees planted with structural soils or soil cells should be:

- Species resistant to both dry and saturated soil conditions
- Species able to withstand changes in soil pH, which can change due to the pH of stormwater, the use of road salts in winter, and differences in pH between the site's native soil and the imported structural soil or soil cell fill
- Species that will not outgrow their allotted space and soil volume

MULTIPLE FUNCTIONS OF INFILTRATION TRENCHES

INFILTRATION TRENCHES AS AN AIR-CONDITIONING CONDENSATE- DISTRIBUTION SYSTEM

Air-conditioning condensate is atmospheric water that condenses on the cold evaporator or coil of an air-conditioning unit. Condensate is minimal when air is very dry, but can be substantial when air is humid. In the relatively humid climate of Austin, Texas, as a rule of thumb you can collect from 0.1 to 0.2 gallons (0.37 to 0.75 liters) of condensate per ton-hour of actual air-conditioner run time.[13] This can add up to 2,000 gallons (7,580 liters) of condensate per day at a large commercial air-conditioning unit in Austin.[14] A growing number of commercial sites in Texas use this water along with harvested rainwater to irrigate their landscapes.

Condensate can be directed to any water-harvesting earthwork, and works particularly well with an infiltration trench if local ordinances require the condensate to be drained subsurface.

REAL-LIFE EXAMPLES OF INFILTRATION TRENCHES

PUMICE WICK TURNS STORMWATER LIABILITY INTO AN ASSET—NORTHERN NEW MEXICO

Too much water in too small an area—that was the problem Jeremiah Kidd of San Isidro Permaculture was hired to solve. He was shown a small north-facing courtyard that would get flooded with runoff from the adjacent home's roof, creating a mud pit in summer and an ice rink in winter. Infiltration trenches with pipe were the answer. Drain boxes were installed at the base of each canale draining into the courtyard, then covered with cobble and gravel (similar to figs. 5.7A, B). Non-perforated pipes were installed to direct the roof runoff from the drain boxes through the courtyard's perimeter garden wall to an infiltration trench irrigating a row of young cottonwood trees acting as a windbreak for the home (similar to fig. 5.9A). The courtyard no longer floods or freezes, and the storm-water liability is now an on-site resource that grows with the trees.

INFILTRATION TRENCH HELPS TRANSFORM AN ERODING DRIVEWAY INTO A PERMEABLE GREEN SPACE— SANTA FE, NEW MEXICO

Ben Haggard once had a long, sloping, dirt driveway that acted like a drainageway. It was bleak to look at, took up half his yard, and in storms it drained both the driveway's surface, and the yard's runoff and topsoil to the street.

Now Ben has converted the driveway into an alluring sponge that infiltrates water, grows plants, builds soil, and adds value to his home (fig. 5.15). The driveway has been reduced to a two-car parking area the length of an average car. The graveled parking area slopes not to the street, but to a pipeless infiltration trench on the other side of two railway ties that act as wheel stops. There the infiltration trench doubles as a permeable path people can use as they walk around the front of the parked cars. A dry-stacked terrace wall made from salvaged pieces of concrete sidewalk rises from the house side of the infiltration trench to a mulched basin in which a young oak tree has been planted. The terrace eliminates the old slope of the driveway and, along with newly planted vegetation, blocks the house from headlights and increases privacy. The terrace basin, infiltration trench, gravel parking surface, and a contour berm placed above the terrace work together to infiltrate runoff throughout the front yard. This passive irrigation supports low-water-use,

wildlife-attracting native plants including oak, rabbit brush, sage, datura, native grasses, and penstemon on 15 inches (381 mm) of average annual precipitation at 7,000 feet (2,133 m) elevation. It's a landscape that creates a sense of place unique to Santa Fe.

Fig. 5.15. The driveway has been cut down to the length of a car and the width of two. It is paved with porous open-graded aggregate, and sloped toward the base of the terrace retaining wall where an infiltration trench infiltrates any runoff. The terraces, rain- and greywaterirrigated vegetation, and metal trellis help screen out headlights at night. Ben Haggard residence, Santa Fe, New Mexico

Closer to the house, apricot, crabapple, and Chinese jujube trees planted in mulched basins increase diversity and grow food. Household greywater augments their irrigation. This simple utilization of on-site water has softened and enriched the house by bringing life and appeal to its surroundings, and it joyfully lures visitors up the winding mulched path through it all.

CHAPTER 6

Imprinting

WHAT IS IMPRINTING?

Imprinting can be done by machine, by hand, or with herding animals. It is a water-harvesting technique used to accelerate the revegetation of disturbed and denuded land by creating numerous small well-formed imprints or depressions in the soil that collect seed, rainwater, and fertile organic matter. At the same time, imprints provide sheltered microclimates for germinating seeds and establishing seedlings (fig. 6.1). Ideally, each imprint captures enough water to germinate one or more seeds and to sustain their growth. Imprints have enough water-storage capacity to increase infiltration to levels that exceed most dryland rainfall rates, thus greatly reducing runoff and associated erosion (fig. 6.2A, B). As vegetation grows in imprinted areas, plants—along with more diverse and abundant soil life—can create a permanent water-harvesting solution in the form of a *living sponge.* This living system increases infiltration still further, decreases erosion, and continually reseeds and regenerates itself.

Fig. 6.1. Bulldozer pulling an imprinting roller. Imprints are in the foreground.

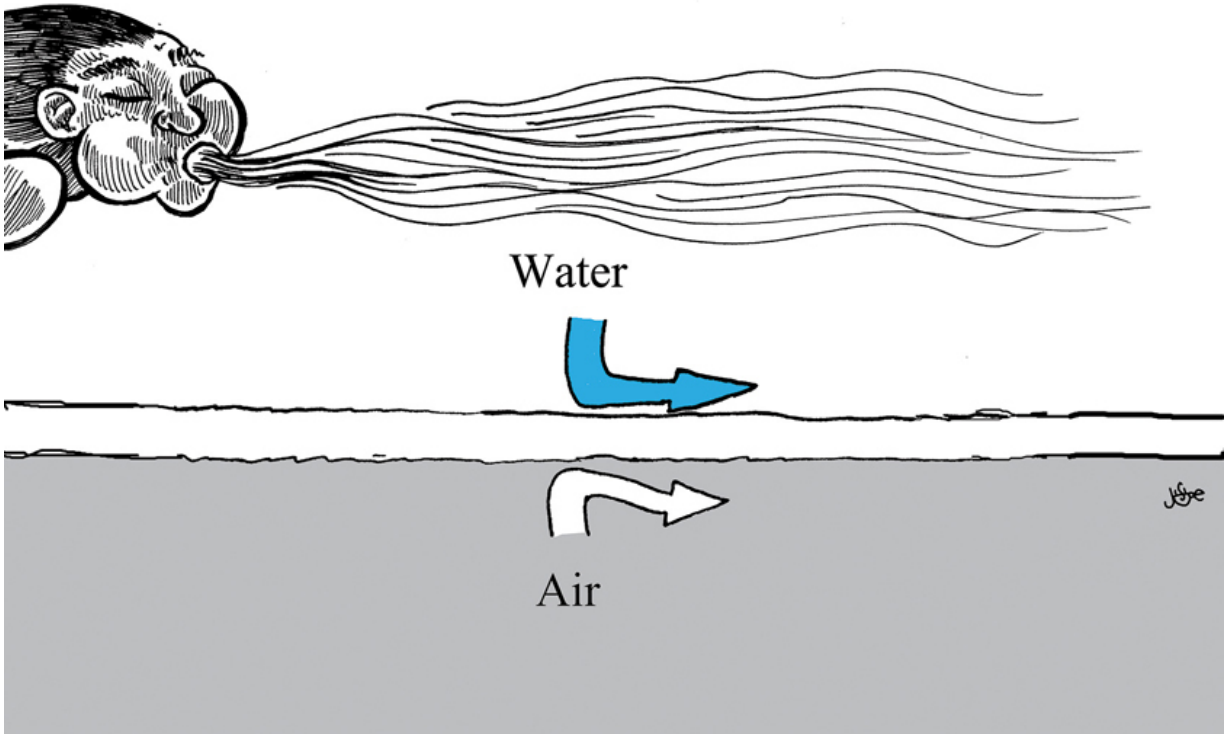


Fig. 6.2A. Exposed, compacted soil encourages erosive runoff and exposes soil and seedlings to the full force of drying winds.

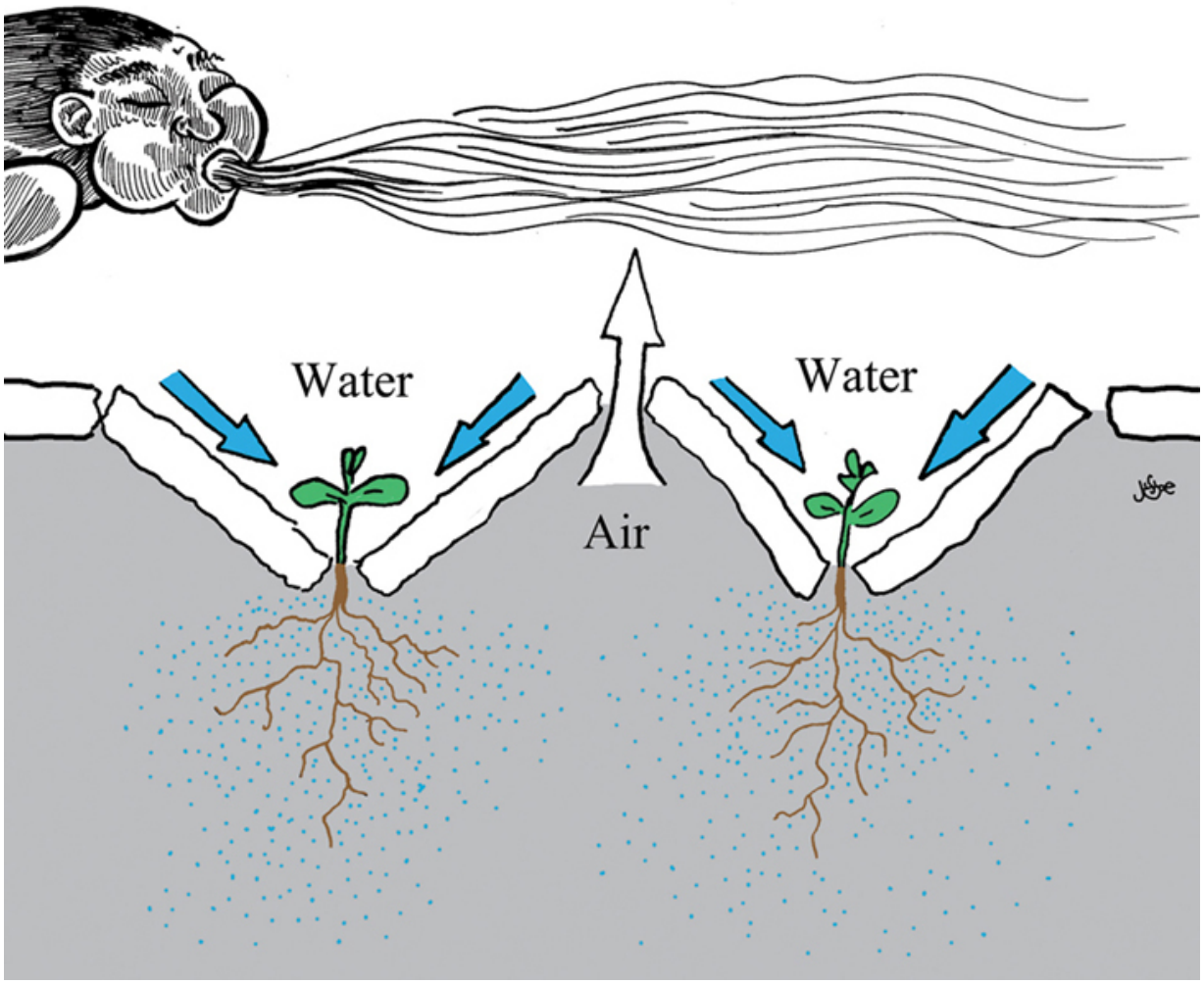


Fig. 6.2B. Imprinted soil encourages infiltration of water and shelters seedlings.

Of all the strategies described in this book, only imprinting is primarily intended for large areas [1 acre (0.4 ha) or more] of *already degraded and denuded land*—not urban backyards. Homeowners, landholders, ranchers, and farmers in rural drylands can use imprinting to restore—or enhance production of— dry-farmed fields and rangelands, to control dust, and to suppress weeds (in particular tumbleweed). Imprinting has also been used to restore land disturbed by mining and highways, and reverse impacts around housing developments (as the Real-Life Example demonstrates).

Unlike more invasive practices such as disking, tilling, or pitting, mechanically-induced imprints are created with downward force, like footprints. This process does not invert the soil's surface, uproot or cover

plants, or destroy beneficial soil life such as cryptogamic crusts and mycorrhizae. The best mechanically made imprints are V-shaped and are made using an imprinter roller, though hoofprints, hand-held shovels or hoes, slow-moving deep-knobbed wheels, or bulldozer tracks can create somewhat similar effects.

Imprinting works simultaneously on two scales. A single imprint is a tiny microbasin approximately 1-foot-square in size and shape. On the large scale, multiple imprints combine to create a water-harvesting surface over a considerable area. One mechanically imprinted acre contains 43,560 imprints (107,600 imprints/ha) (fig. 6.3).

Fig. 6.3. Fresh imprints

The first part of this chapter focuses on imprinting using a machine. The Variations section focuses on imprinting by hand or with herding animals.

Research soil scientist Bob Dixon invented mechanical imprinting in 1976. His coworker, restoration ecologist Ann Carr, continues to enhance its effectiveness as a no-till method of seeding and restoring degraded drylands.

Since Bob and Ann are the experts on this strategy, most of this chapter is based on their consultations and publications.[1,2,3]

WHERE IS IMPRINTING USED?

Imprinting is appropriate for use on abandoned farm fields and building sites, overgrazed rangeland, soils with rock up to 1 foot (30 cm) in diameter, and slopes as steep as 2:1. This technique is particularly useful for establishing vegetation on degraded lands with annual precipitation ranging from 3 to 14 inches (76 mm to 356 mm).

Imprinting is typically used in rural areas. Sites should be at least an acre (0.4 ha) in size to justify the expense of bringing in the imprinting equipment or managing livestock using mobile fencing. Imprinting is typically used by ranchers, transportation departments, developers, farmers, and others looking to restore larger denuded acreages.

TOOLS AND MATERIALS

Basic tools: an imprinter roller and a tractor to pull it. Some areas may have commercial imprinting services. A later section in this chapter describes the construction of imprinter rollers. If an imprinter roller is not available, a bulldozer with deep tracks, densely herded hoofed animals managed within mobile fencing, or a community of people working together with hand tools, could be used instead.

Materials: diverse seed mixtures of perennial and annual native plants for restoration projects. A seed mix of perennial and annual crops grows well in alternating dry and wet conditions with compost added for dry-farming projects. Seed distributed using a seeder box on an imprinter should be mixed half and half by volume with wheat bran to evenly distribute seeds throughout the mix.

IMPLEMENTATION STEPS

SITING

After you've determined that your site may be suitable for imprinting, there may be additional strategies to implement to make your investment of time and money worthwhile. Walk your site; survey it.

Consider the slope and the condition of the watershed. You may be confronted with large volumes of fast-moving, sediment-laden water washing across the site during intense rainstorms, especially if land above your site is sparsely vegetated or steeply sloped. If land slope, soil texture, and access are suitable for imprinting, start at the top of the watershed. This may be sufficient to stop erosion and revegetate the land. However, imprints can be washed out by heavy runoff flowing from upslope.

Therefore, if imprinting is not feasible for use at the *top* of your watershed, first create a series of contour terraces, berm 'n basins, or diversion swales that intercept runoff, then conduct imprinting lower in the watershed. It may also be possible to intersperse terraces and contour berms between sections of imprinting to further slow runoff, increase infiltration, and decrease premature erosion of imprints. Survey the site and mark where each strategy is to be implemented.

SPACING AND APPROPRIATE SIZE

Each imprint can hold about 1 gallon (3.8 liters) of water on level land. They are created by the protruding angle irons welded to an imprinter roller, which are called their "teeth." These imprinting teeth are staggered about 1 foot apart from center to center throughout the roller. The individual imprints they create are about 4 to 7 inches (10 to 18 cm) deep, 10 inches (25 cm) long, and 8 inches (20 cm) wide.

CREATING IMPRINTS

To undertake imprinting, you will need to obtain an imprinting device or contract with a commercial imprinting service. Information on the availability of imprinters and their manufacture is available at The Imprinting Foundation's website: Imprinting.org. See appendix 4 for further contact information.

For treating large acreages, an imprinting roller with a seeding attachment is the tool of choice since it evenly distributes seed as it creates long-lasting

imprints. Imprinting rollers equipped with staggered 1-foot-square (30 cm) imprinting teeth are designed to be non-directional with respect to slope. However, on steep slopes it's best to pull the imprinter up and downslope rather than across slope for the safety and comfort of the operator (fig. 6.4). This also reduces wear and tear on equipment.

Fig. 6.4. Imprinting a steep slope

The growsers or cleats on bulldozer tracks can imprint soil if you do not have access to an imprinter roller. But imprinting with a bulldozer requires traveling back and forth across the land many times because of the narrow bulldozer tracks. Run the bulldozer up and down-slope so the imprints made by the growsers are aligned on land contour. A standard bulldozer track makes a small, less than adequate imprint; however, a bulldozer equipped with self-cleaning tracks makes imprints that are comparable in size and capacity to imprinting rollers (fig. 6.5). They work well on steep slopes and in wetlands; however the availability of this special purpose track is limited.

Fig. 6.5. A bulldozer with self-cleaning tracks

Cattle can sometimes be used to create imprints, though hoofprints may be shallow unless the soil is soft or moist. Temporarily fence off the area to be imprinted, bring in the cattle, then promptly remove them once the soil is thoroughly imprinted by their hoofs. See Variations section for more.

Whatever your imprinting device, make your imprints deep enough to intercept substantial runoff and hold sufficient water for seed germination. Shallow imprints disturb the land without creating sufficient water storage capacity to assist much with seed germination. In addition, the roller core of an imprinter should be at least 20 inches (50 cm) in diameter. Smaller diameter imprinters generate more of a shearing force than a downward force, rounding off and obscuring imprints rather than making them deep and firm. This creates excessive soil disturbance, a condition favoring germination of annual weed seeds.

Each of the resultant *imprinted* microwatersheds is about 1 foot (30 cm) square, and can hold 0.8 to 1.3 gallons (3 to 5 liters) of water per imprint on level ground—this will retain all the water from a 2- to 3.5-inch (50 to 88 mm) rainfall.

CONSTRUCTING AN IMPRINTER ROLLER

If a local imprinting service is not available, you may want to build a community imprinter roller. Ranchers using homemade imprinters have seeded perennial grasses on some 50,000 acres (20,000 ha) of degraded rangeland in southern Arizona alone.[4]

An imprinter roller can be fabricated from a used 10- to 20-foot (300–600 cm) long, 20- or 24-inch (50–60 cm) diameter smooth roller, which can be purchased at farm auctions for around $200. Weld 10-inch (25 cm) lengths of 6 X 6 inch (15 cm) to 8 X 8 inch (20 cm) angle iron onto the roller in a pattern of staggered star rings (fig. 6.6). Leave a 2-inch (5-cm) gap between the rings and between each piece of angle iron. This 2-inch (5-cm) gap around the base of each angle iron tooth improves penetration into the soil while providing a berm around each imprint to hold rainwater in place until the water infiltrates into the soil.

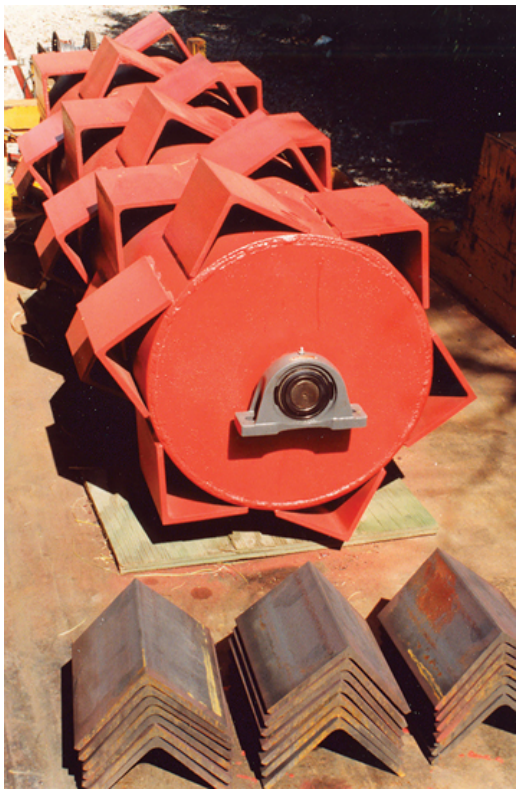


Fig. 6.6. The roller core of an imprinter with alternating star rings of angle iron

By staggering the imprints you prevent the formation of rills and gullies. Additionally, alternating imprints reduces ant predation since there is no continuous rill or furrow they can follow like a highway to the seed buffet.

Fabricate a rectangular tow frame to allow you to pull your imprinter roller with a tractor. The tow frame should be built from square tool bars that permit the use of commercial tool clamps to attach hitches and accessories. Make the

front and rear of the tow frame identical so hitches can be attached to either front or rear to reverse the direction of rotation of the imprinter roller. This doubles the life of the imprinting teeth because they wear on their leading edges.

As mentioned in the planting/seeding section, weights can be temporarily added to the tow frame at the axle level or slightly below the axle level to create sufficient weight to increase the depth of imprinting in more compact soils. This is similar to the way suitcase weights are used to add ballast to the front end of farm tractors.

Install a seed box at the top of the imprinter roller in such as way that a well-mixed and controlled amount of seed drops onto the roller as it rolls forward, allowing it to imbed seeds into the soil at the same time it forms the imprints.

Some variations for special imprinters are described later. Contact The Imprinting Foundation for further specifications for constructing and using an imprinter and tow frame (appendix 4).

LOCATION AND CONSTRUCTION OF APPROPRIATE SPILLWAY(S) FOR OVERFLOW

Imprinting makes many small depressions in a slope, but does not change the overall slope of the landscape. The direction excess water flows after imprinting is the same as before imprinting, thus spillways are not needed.

PLANTING/SEEDING

Select a seed mix of species adapted to the site's climate and degraded soil. Native plant species are best adapted to thrive in the natural conditions of your area. Avoid the use of any invasive exotic species such as buffelgrass (*Pennistemum ciliare*) in the Americas. Diversify your seed mix by incorporating species that germinate in different seasons and under different conditions. About one-fourth of your seed species should be fast-growing hardy pioneers that prefer exposed, disturbed soils. They provide quick shade and create conditions for the germination of seed from plants preferring less exposed soils. In severely degraded sites and areas where grazing is a land management goal, Bob Dixon often recommends incorporating exotic annual barley and ryegrass since the seeds are cheap, readily available, and germinate

quickly to stabilize the imprints and increase soil fertility. The remaining three-quarters of your seed mix should be hardy perennial plants. On average, 10 to 15 pounds (4 to 6 kg) of seed is used per acre (0.4 ha) of imprinted land.

To uniformly mix and discharge seeds of diverse size and shape, Bob mixes his seed half and half with wheat bran—an inexpensive by-product of white flour milling. The flaky bran prevents fluffy low-density seeds from migrating upward in the seeder box, and keeps the smooth high-density seeds from moving downward, thus ensuring a vertically uniform mix. Bob's seeder box is attached to the frame of the imprinting roller, just before the roller. Thus, the imprinter presses the seeds into the soil, lessening predation by insects, rodents, and birds before germination. A seeder could also be rigged to a bulldozer. If seeders are not attached to either the imprinter or bulldozer, seeding can be done with a seeder mounted on a tractor that runs in front of a second tractor pulling the imprinter. If you are using cattle to do the imprinting, broadcast seed by hand or with a hand-cranked seeder strapped to your body just before the cattle create the imprints.

Note that farm seeders and planters are designed for uniformly shaped seeds that flow evenly through discharge ports, like sand through an hourglass. Native seed mixes with their diverse sizes and shapes do not flow evenly, therefore a mechanical device called a seed agitator is needed to push the seed mix through the discharge ports. Because of this, commercial seeders often need to be modified to uniformly scatter native seed mixes.

For seed sources in your area, check with your regional or state native plant society for reputable distributors. You can also inquire with the Plant Material Centers of the Natural Resource Conservation Service (NRCS), United States Department of Agriculture, which maintain lists of seed sources. Or look in the yellow pages under "Seed." In my area Wildlands Restoration (tel: 520-882-0969) is often my preferred supplier.

Time your imprinting and seeding so seeds are in place before local rain and germination seasons. Here in the Sonoran Desert, Bob prefers to seed in the fall to capitalize on the gentle winter rains that soak into the soil, rather than the violent summer rains that might erode or flatten imprints and run off the soil's surface. Fall seeding also lets Bob use native cool-season-germinating species such as perennial four-wing saltbush (*Atriplex canescens*), annual Indian

wheat (*Plantago purshii*), and exotic annual barley and ryegrass that sprout quickly and rob light and soil moisture from fall-germinating Russian thistle (*Salsola iberica*) and exotic warm-season-germinating weeds. Saltbush continues to grow as temperatures rise, while Indian wheat, barley, and ryegrass complete their life cycles in the spring, allowing warm season natives to colonize the improved soil within the decomposing plant material. With this approach, desirable native vegetation has a good chance of becoming dominant and stabilizing the imprints.

The odds of getting good germination rates of native seeds and survival of seedlings is improved by imprinting, but ultimately success depends on the timing and volume of rainfall and the duration of conditions that promote germination and seedling growth. It is important to be patient when seeding, and to take heart in the small triumphs until conditions are ideal for good germination. Some portion of the seeds will survive in the soil until that particular year when conditions are finally ideal. In the meantime, imprinting will reduce erosion, increase soil stability, and provide competition for nonnative invasive plants such as tumbleweed. Imprints and seeds are designed to wait for up to five years for good rains to occur.

If soil is so compacted the imprinter cannot make adequate depressions, you may want to delay imprinting until a week after a good rain has penetrated the soil. Adhering to this sequence will make imprinting more effective because the soil will be soft enough to create deep imprints, but not so soft the surface is unsuitable to bear the weight of heavy equipment. On sandy sites where the wind could erode unstabilized imprints, you may want to wait until the soil is damp to conduct imprinting so the imprints will form a slight crust and hold their form once they dry. Alternatively, if you imprint right before the onset of a rainy season, even imprints made in very dry sandy or silty soil will consolidate once the first good rain falls on them.

The pressure exerted by a standard imprinting roller can be adjusted between 15 and 30 pounds per square inch (psi). The 15 psi (1.05 kilogramforce/cm^2) is created by the basic weight of the imprinter, which is 500 pounds (225 kilograms) per foot (30 cm) of roller length. Additional weight, up to 500 pounds per foot, can be loaded on the imprinter frame to achieve up to 30 psi (2.10 kilo-gram-force/cm^2).

Most hard, dry soils can be imprinted with 30 psi of imprinting force; however, some especially hard soils may require softening by ripping or rain first.

MAINTENANCE

Keep cattle, all-terrain vehicles, and other disturbances off imprinted areas until vegetation has become well established. Then manage the land carefully to prevent it from becoming degraded again.

Check your imprints periodically, especially during or just after big rains. You may need to create contour terraces or berm 'n basins to manage runoff on slopes if heavy runoff washes imprints away. Once you have added these earthworks to manage large volumes of runoff water, re-imprint the land between them.

VARIATIONS FOR SPECIAL MECHANICAL IMPRINTERS

Imprinters for steep slopes should be made with angle iron bent to a narrower angle to create a more effective microbasin shape (fig. 6.7).

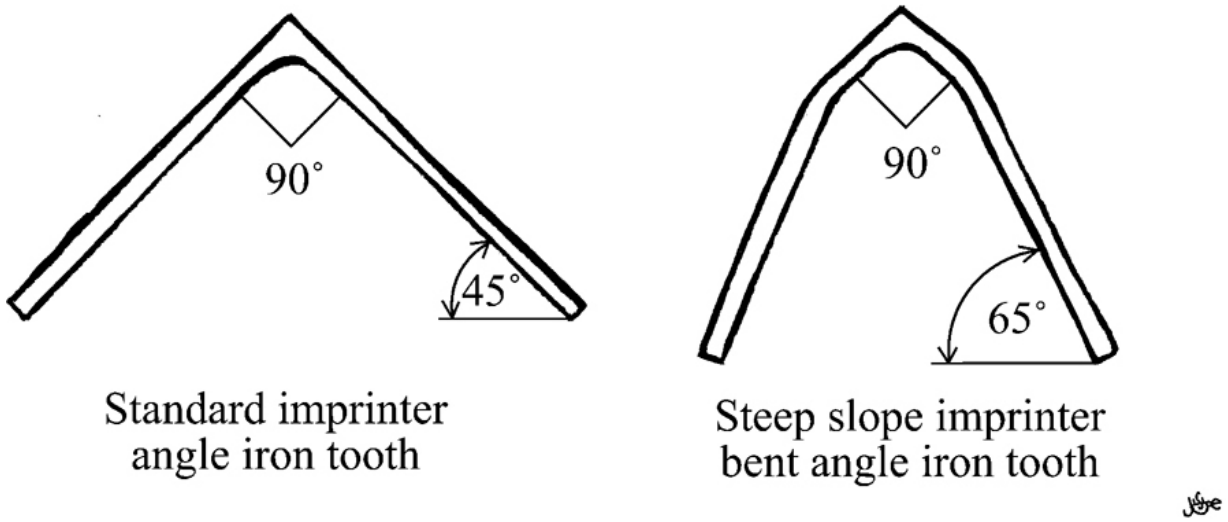


Fig. 6.7. A standard imprinter angle iron tooth, left. A steep-slope imprinter angle iron tooth made by pressing the legs of the angle iron together, right

Imprinters for rocky land should be made with steel that is at least 1/2 inch (1.25 cm) thick for the roller core and angular imprinting teeth to reduce the

potential for bending on impact with large rocks.

NON-MECHANICAL VARIATIONS OF IMPRINTING

IMPRINTING BY HAND— ZAI PLANTING PITS

Many thanks to ECHO and their technical note #78 "Zai Pit System" by Tim Motis, Chris D'Aiuto, and Brandon Lingbeek from which much of the following was drawn.

Zai or "tassa" pits are indigenous water harvesting strategies from Burkina Faso and Niger (fig 6.8). These hand-dug planting pits—typically 8 to 12 inches (20-30 cm) in diameter, 4 to 8 inches (10-20 cm) deep, and spaced 24 to 35 inches (60-90 cm) apart—are used to grow annual crops irrigated solely with rainfall and stormwater runoff.[5] Dirt removed from each pit is used to make a crescent-shaped berm on its downslope side that increases water harvesting capacity and protects seedlings from wind. Seed is planted within each pit then two handfuls of compost or aged manure are added to cover the bottom (figs 6.9A to C).

Fig. 6.8. Millet growing in zai pits in Burkina Faso. Photo: Hamado Sawadogo.

Fig. 6.9A. Marking lines on the ground to indicate rows were zai pits are to be dug. Photo: Hamado Sawadogo

Fig. 6.9B. Digging zai pits. Photo: Hamado Sawadogo

Fig. 6.9C. Aged manure and compost being placed into the pits. Photo: Hamado Sawadogo

Land sloping 3 to 5% is ideal for this strategy— erosion is greater on steeper slopes and water already gathers on flat land.[6] In this context, the pits capture water and nutrients that would otherwise wash or blow away, with clear benefits. In dry-farmed areas of Niger, millet yields that were often less than 350 kg/hectare without zai pits increased up to 1,000 to 2,000 kg/ha with zai pits.[7]

This strategy requires significant labor, so work is typically done in the dry season when labor constraints in small landholder agricultural communities are minimal. Establishing 8,000 to 10,000 pits/acre (20,000-25,000 zai pits/hectare) can take 120 to 180 hours/acre (300 to 450 hours/hectare) to dig the zai pits plus another 100 hours/acre (250 hours/hectare) to fertilize them. These numbers vary depending on the size and spacing of holes.[8] Even given the high labor inputs, in the highlands of Ethiopia farmers earned 20 times more income than the labor costs of digging the pits.[9]

P.D. Kaboré and C. Reij report that "…farmers dig pits in year one. Two to five years later, many farmers dig new pits in between existing pits… On shallow or sandy soil that is not heavily encrusted, the pits are often

maintained on a more or less permanent basis. When using the same pits year after year, the soil/debris that fills up the pits over time is cleared to prepare for planting each growing season."[10]

The best plants for seeding within zai pits are those that grow well in alternating dry and wet soil conditions, such as sorghum and pearl millet. Zai pit trials in South Africa indicated that the combined grain yield of nitrogen-fixing cowpea plus sorghum was as much as three times higher than sorghum alone.[11]

Integrating zai pits with additional water-harvesting strategies such as contour berms/bunds of rock (fig. 6.10) and intercropping with beneficial trees (such as nitrogen-fixing, livestock fodder-producing legumes) and other perennial crops enhances their effectiveness even more. For example, in Malawi trials of maize/corn alley-cropped between leguminous gliricida trees and mulched with prunings from those trees produced three times as much as unfertilized fields lacking the intercropping with trees.[12] The carbon sequestration and erosion control resulting from such tree intercropping also contributed to this strategy being ranked in the book *Drawdown* as number 17 out of its top 100 strategies to drawdown carbon in the atmosphere and reverse global warming.[13]

Fig. 6.10. Zai pits integrated with contour rock berms/bunds. Photo: Chris Reij

IMPRINTING WITH ANIMALS— INTENSIVE, SHORT-DURATION HERDING/DUNGING/URINATING

By the Savory Institute, Savory.Global

Consider using animals to do what an imprinter does, but without fossil fuels and for a fraction of the cost—which really does matter on extensive land areas. For thousands of years, people have observed the trampling effects of their animals over many days or months and the damage this causes to the land, so recognizing the beneficial effects of even higher amounts of trampling, dunging, and urinating for short times—to kick start land recovery—initially requires a significant change in thinking.

In seasonal rainfall environments, deliberately concentrating and moving relatively high numbers of large herding animals—as their wild ancestors naturally moved in the presence of pack-hunting predators—is vital to maintaining the health of lands we once thought they destroyed. While bunched as a herd, animals step recklessly. As a result, even very coarse plants that contain old dead material that would not normally be grazed or trampled is trampled down. This provides cover for the soil surface. In addition, the hooves of bunching and milling animals leave the soil chipped and broken. In effect, the animals do what any gardener would do to get seeds to grow: first loosen the sealed soil surface, then bury the seed slightly and compact the soil around the seed, then cover the surface with mulch.

Figs. 6.11A-E show the fairly dramatic response to this strategy in Zimbabwe over a period of three years on land managed by the Africa Center for Holistic Management near the Victoria Falls. The land had deteriorated badly following decades in which a small herd of cattle (100 head) had been allowed to wander and the vegetation was frequently burned. When the first photo was taken, the soils were bare and the surfaces had been sealed (or "capped") for more than thirty years. The belief was that grass couldn't grow under the trees. The ranch lies in a seasonally humid environment that averages 26 inches (650 mm) of rain that comes over a period of about five months. Even though many wildlife species are present—including predators—the wild grazers no longer function

naturally and had not disturbed this area enough to break the soil capping and allow new plants to germinate.

Fig. 6.11A. Before the land was impacted by intensive, short duration herding/dunging/urinating of the cattle, Zimbabwe, October 2005. Photo: the Savory Institute

Fig. 6.11B. After the herd spent each night for a week within a lion-proof enclosure on the site, breaking up the sealed soil surface and depositing dung and urine, October 2005. Photo: the Savory Institute

Fig. 6.11C. Response to the animal impact in the following rainy season – a profusion of annual grasses, February 2006. Photo: the Savory Institute

6.11D. Mass of fungi also came up within the impacted area—but not elsewhere, February 2006. Photo: the Savory Institute

6.11E. Three years from initial impact and the first perennial grasses are coming in. Soil remains covered through the dry season, October 2008. Photo: the Savory Institute

The land managers were already using holistic-planned grazing to coordinate herd movements with plant recovery rates. So to address this problem, they decided to concentrate their herd of about five hundred cattle on this degraded site. They did so by placing a movable predator-proof enclosure around the site for about a week, concentrating the whole herd within it each night after they had spent the day grazing nearby. As a result, there was sufficient impact to break the capped soil surface, and that, plus the infusion of dung and urine, was enough to get grass growing again—in this case annual grasses. The next year, the additional soil cover provided by the new plants and plant litter helped to grow enough new grass, including a few perennials, to cover much of the bare ground. This occurred without further treatments and even though wild grazers began to frequent the area.

The use of the closely-bunched cattle herd provided the kick start needed for this biological community to move forward without reseeding or other assistance. The managers have repeated this treatment now on nearly five hundred additional sites. Annual grasses usually dominate the first successional advance, but perennial grasses begin to appear in about the third season and continue to increase in numbers in following years in a pattern that has become familiar to those using "animal impact" to reclaim bare ground.

MULTIPLE FUNCTIONS OF IMPRINTING

IMPRINTING FOR DUST CONTROL AND RESTORATION OF DESERT SAVANNAS

Areas denuded by blading, overgrazing, or conventional farming often suffer from dust pollution and soil erosion due to the destabilization of the soil and resulting increase in runoff. These problems are compounded when lands are abandoned in a debilitated state. Imprinting and seeding speeds the restoration process of the degraded watershed.

IMPRINTING AS WEED SUPPRESSION

An imprinter can be rolled over invasive weeds such as tumbleweed or Russian thistle (*Salsola iberica*), flattening and partially imbedding the plants into the imprints to create a water-saving, soil-enriching mulch. Ideally imprinting should occur while the weeds are still immature and do not have viable seeds on them (this depends on rainfall, sometime in spring).

Mulch is very helpful for promoting water infiltration because it supports surface feeders such as pill bugs, solitary bees, termites, and ants that bore holes into the soil. Mulching weeds with an imprinter turns a problem into a resource (fig. 6.12).

Fig. 6.12. An early style of imprinter squashing tumbleweed so it acts as a mulch for the imprints

Most weeds such as Russian thistle thrive in disturbed and exposed soils. Imprinting minimizes further soil disturbance and turns weeds into soil-sheltering mulch, where "late successional" plants, such as perennial grasses, shrubs, and trees, can germinate in the shelter of the imprints and mulch. Russian thistle will continue to grow, but as long as the soil is not disturbed again, other plants from the imprinted seed mix will begin to dominate. It may take five years to notice much change, but once you've seeded and imprinted, you need do little more than wait.

REAL-LIFE EXAMPLE OF IMPRINTING

RESTORING BLADED LAND— MARANA, ARIZONA

In the mid 1980s, the developers of the Continental Ranch housing development leveled, straightened, and walled a 5-mile (8-km) stretch (592 acres or 240 ha) of floodplain along the Santa Cruz River in Marana, Arizona. Such severe disturbance accelerated storm runoff, erosion, and downstream sedimentation, while greatly increasing dust pollution (fig. 6.13).

Fig. 6.13. Dust storm caused by denuded land, Marana, Arizona

The entire area was imprinted and seeded with a complex native-seed mix of early-, mid-, and latesuccessional species to accelerate establishment of a stable plant community with biodiversity equal to or greater than relatively undisturbed areas nearby (fig. 6.14A).

Fig. 6.14A. Imprinting and seeding

Within one year a mat of vegetation started to reestablish on below-normal rainfall. Three years later the soil was well vegetated, fully resolving the on-site dust pollution problem (fig. 6.14B). Today, a dense groundcover of shrubs and trees is established on nothing more than 10 inches (254 mm) of average annual rainfall infiltrated into the soil imprints.

6.14B. Post-imprinting

See video footage of a similar imprinting project in the drylands section of the four-part *Global Gardener* video (Bullfrog Films, BullfrogFilms.com; more information in appendix 4).

BULLDOZER TRACKS USED FOR IMPRINTING

See Rolling Dip Dirt Road Drains in the Variations section of chapter 9.

CHAPTER 7

Mulching

WHAT IS MULCHING?

Mulching is the application of porous materials such as compost, aged manure, straw, woodchips, or gravel onto the *surface* of the soil (box 7.1). These mulch materials, and others, are described under Tools and Materials, for mulch need not be the purchased bagged "bark chips" synonymous with mulch for so many people. Mulch can be creative! And, mulch is especially appropriate for small urban and suburban lots.

Box 7.1. What Mulch Is *Not*

A harmful practice in the dryland environment is laying plastic over the soil to discourage weed growth, then covering the plastic with a layer of gravel. Plastic is not porous. It dehydrates the landscape by preventing rainfall from infiltrating into the soil. Ironically, it encourages the growth of molds beneath its surface, which coupled with the dehydrated soils can lead to the death of landscape plants it surrounds. Plastic does discourage weeds, but it also discourages many beneficial life forms. It is not a true mulch.

Mulch is both a spongy welcome mat luring water into the soil and a sheltering cover reducing soil-moisture loss to evaporation, and thus it's great when placed in the basins of earthworks (figs. 7.1A, B). Mulch also limits soil erosion and weed growth, delineates planting areas, can act as a deodorizer for livestock pens and fruit-tree urinals, and improves soil fertility. (See the "Mulching As More Than a Water-Harvesting Strategy" section later in this chapter for more on these applications.)

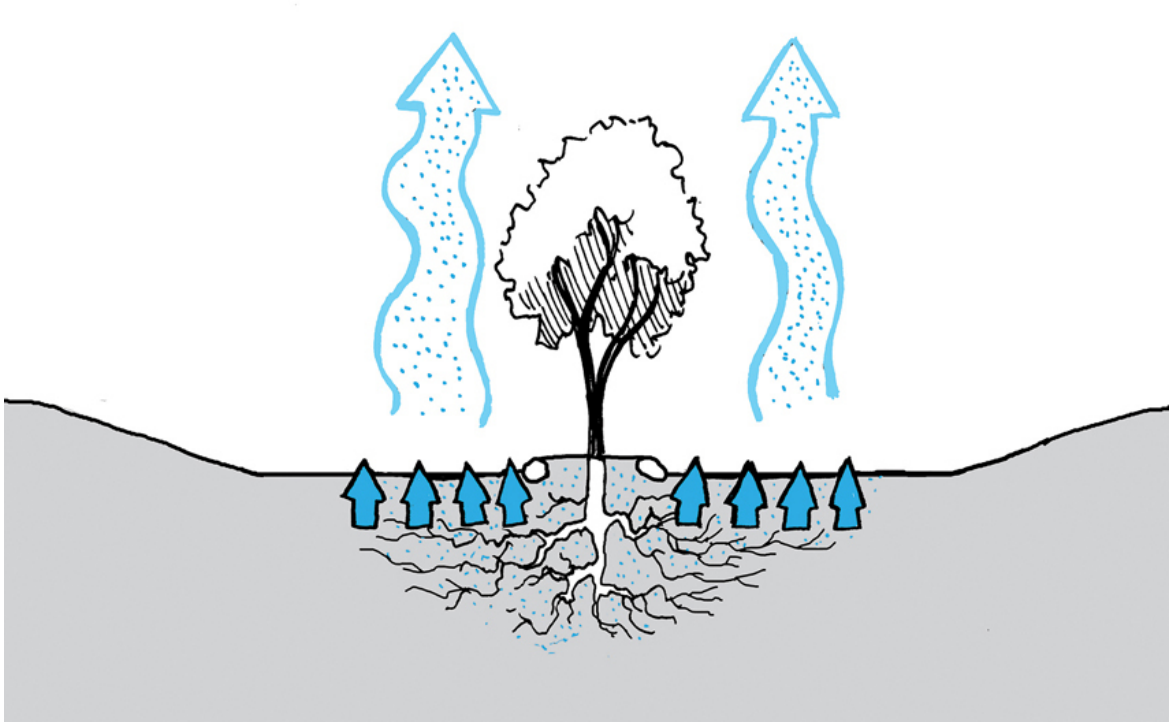


Fig. 7.1A. Bare earth, high evaporation, small tree. A basin without mulch losing most of its soil moisture to capillary action and evaporation.

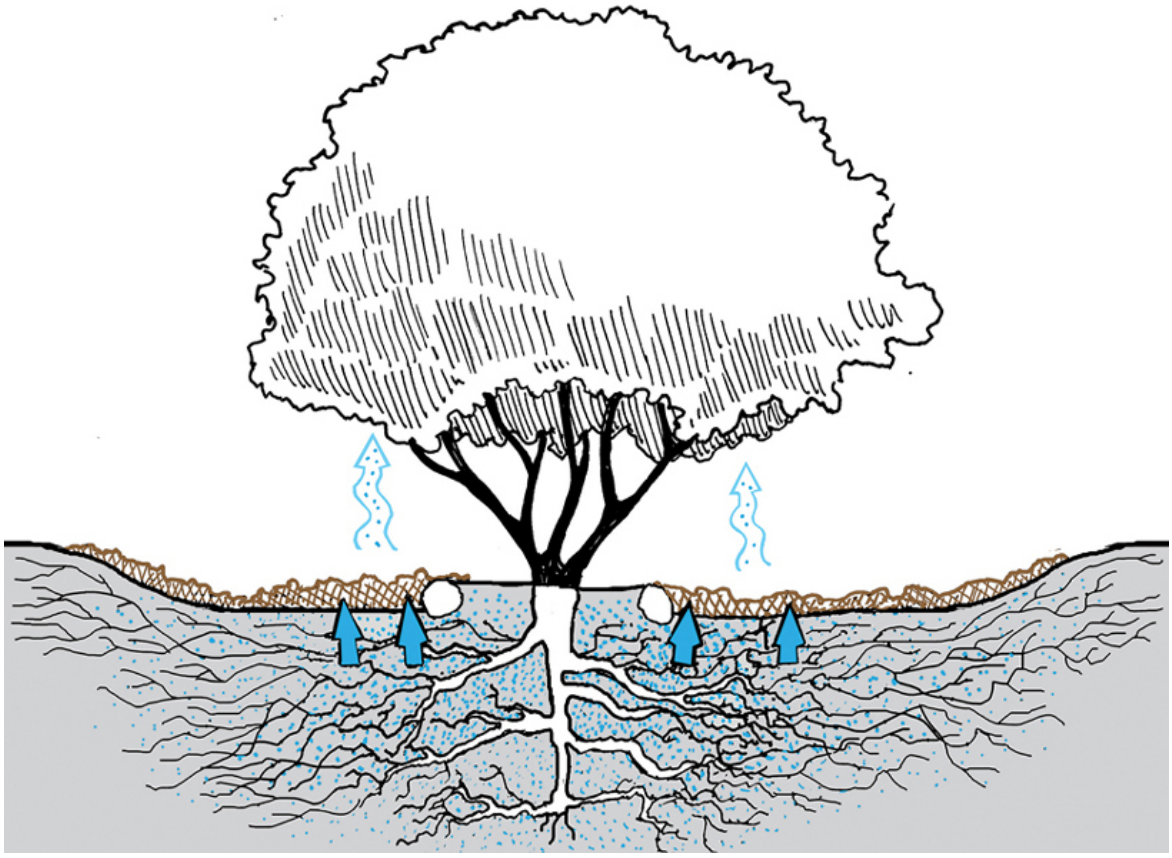


Fig. 7.1B. Mulched earth, low evaporation, large tree. The basin mulched for improved infiltration and retention of water in the soil.

Where I want vegetation, I prefer mulches of organic material, such as tree bark or compost, that will more quickly break down and build soil than more permanent mulches, such as rock or gravel. This is very important in home landscapes, especially those of new homes where the topsoil has been entirely bladed away to create a compact building pad devoid of any organic material (fig. 7.2). The application of organic mulches speeds up the rate at which water-absorbing topsoil and fertility are brought back to a disturbed site, it makes digging easier by lessening the compaction and dryness of the soil, and it encourages you to allow fallen leaves to remain on site, under and around vegetation, as a naturally renewing source of more mulch. Beneficial decomposition/transformation of that organic matter into more vibrant soil and life will then beneficially speed up within your earthworks thanks to the harvested waters—a virtuous cycle!

Fig. 7.2. Bladed building pads. The relatively healthy, sponge-like watershed of established vegetation and topsoil, in the foreground, has been bladed and compacted below (background) to create a sterile and water-phobic watershed.

Gravel or rock mulches create a more permeable surface than bare earth but, by themselves, do not add fertility to the soil in our lifetime. What's more, gravel mulches seem to encourage people to rake up any fallen leaves or organic matter to keep the gravel in full view. Thus the site is continually strip-mined of its fertility. Nonetheless, gravel mulches can benefit plants by reducing water loss to runoff, catching organic matter between their aggregate, reducing the digging of rodents, and heating up the soil in colder climates (see the Ancient Hohokam Rock Mulching example at the end of this chapter, and appendix 2 in Volume 1 "Water Harvesting Traditions in the Desert Southwest"). (For more on gravel specifications, see the Tools and Materials section.)

Mulch is placed on the *surface* of the soil. It is not mixed or dug into the soil, since its porosity would be greatly reduced with soil between its particles. In addition, most organic mulch materials are rich in carbon and, if mixed in the soil, could deplete nitrogen in the soil as they decompose. Nitrogen depletion occurs because microorganisms assisting decomposition need nitrogen to break down carbon, which they get from the surrounding soil. Carbon-rich mulch applied on the soil's

surface decomposes more slowly than if it's mixed into the soil, so soil nitrogen is consumed at a slower rate that does not adversely affect vegetation.

Vertical mulching is an exception to the surface application of mulch. It is a technique that packs organic mulch into open holes or trenches without mixing the mulch into the soil or covering it with earth. Like infiltration trenches, vertical mulching encourages quick penetration and storage of moisture deeper below the soil's surface. What differs from infiltration trenches is the use of organic matter, rather than gravel, as the fill material for the hole. The organic matter itself becomes a storage medium of water along with the soil, and it slowly releases it over time—to the extent that the mulch can still be moist three months after the last big rain event. So vertical mulch is used where you want to concentrate soil moisture beside a plant, and encourage deeper root growth that will utilize the slow release of water harvested within the mulch. Vertical mulching is *used only where there is enough water to periodically saturate the mulch*, such as where incoming runoff water adds to the volume of direct rainfall a planting area receives, or where supplemental irrigation water is applied to the vertical mulch. See the Variations section of this chapter for more.

Among the other techniques discussed in the Real-Life Examples section are recycling dead trees as mulch, and Ruth Stout's "no work" gardens using heavy straw mulch.

Mulch *happens*. See it. Understand it. Mimic it. Benefit from it. Under trees and shrubs in a healthy forest you always find a rich humus created from accumulated leaves, bark, and twigs: mulch. The particles comprising mulch protect the soil from the compacting force of raindrops. They act as countless tiny water-harvesting sponges intercepting those drops before they have a chance to become erosive runoff, and they allow the moisture to infiltrate into adjacent soils.

Once rainwater has infiltrated into the soil, the mulch layer helps retain that precious moisture by greatly reducing the loss of water to evaporation. In drylands, evaporation from the upper 4 inches (10 cm) of soil is typically very rapid. High temperatures, drying winds, and capillary action move water quickly upward within the soil to the surface where liquid water changes to water vapor and moves out of the soil into the atmosphere.[1] Mulch shelters soil and shallow roots, lowering their temperatures in hot climates. This enables earthworms and other beneficial soil life to thrive. These life forms and the mulch build soil as it gradually decomposes into humus. This nutrient-rich humus feeds trees and other plants. Birds and other animals come for the food and shelter offered by the vegetation, and leave little

fertilizing packets of their own in the form of manure. Everything falls to the ground and decomposes to be taken up again by flourishing plant and animal life, creating a wonderfully sustainable nutrient loop.

In the human-built environment, fallen leaves are often snatched up with a rake or hit by a gust from a gas blower, then bagged in plastic, and carted off to the dump. The resulting bare earth is scorched in summer, frozen in winter, and prone to erosion and high evaporation year round. In addition, far less water is absorbed into the soil, and water is more likely to wastefully puddle, because exposed soil often forms a cap-like layer of more compacted, less permeable earth. Advertisers and landscape companies then turn around and sell manufactured fertilizer and imported mulch to replace the free, local nutrients that are routinely removed. You can save work and expense by letting leaves fall and naturally decompose under your plants. Leaves on paths and patios can be raked or swept into sunken basins nearby (compare figs. 7.3A,B with 7.4A,B).

Fig. 7.3A. Strip mining leaves and nutrients results in higher maintenance, higher costs, and smaller trees.

Fig. 7.3B. Maintenance and costs increase with purchased fertilizer used to replace removed nutrients.

Fig. 7.4A. Harvesting leaf-drop and nutrients results in less maintenance, lower costs, and larger trees.

Fig. 7.4B. Relax, and let nature do the work.

WHERE IS MULCH USED?

Mulch is the key to getting more of your harvested water to infiltrate into the soil rather than puddle on top of it. So use it—especially an organic mulch—where you want water to infiltrate into the soil around vegetation and within all basins.

To save material costs and maximize efficiency, prioritize the use of mulch to the more water-rich, intensively used sections of a landscape, within basins or terraces harvesting runoff and/or greywater, rather than spreading it over the whole

landscape. But if you have the materials on hand to cover more surface area with mulch—go for it.

Do not place mulch within drainages or on steep slopes where it will wash away with runoff. However, if the runoff on steep slopes is first checked with vegetation and/or earthworks, mulch might then be used.

TOOLS AND MATERIALS

Tools: work gloves, wheelbarrow, shovel, rake, and pitchfork. A truck, front loader (such as a Bobcat), or backhoe can be used to move mulch materials around large sites.

Materials: Typically the easiest and cheapest way to mulch is to use whatever organic material is at hand. By organic I mean natural, primarily carbon-based materials that break down and improve the soil, such as dead plant material, manure, or compost. Though they are natural, more-durable rock and gravel don't meet my definition of organic mulch.

Common mulching materials are listed below, with notes on their characteristics and availability. This list is not comprehensive; it's just to give you inspiration as to what else you could use. Note that while any of these mulches can be beneficial on their own, high carbon mulches (straw, paper, cardboard, dry leaves) will give you greater benefit if mixed with a nitrogen source (manure, fresh green prunings, compost, grass clippings). This keeps the soil's ratio in balance and provides a greater range of nutrients.

- **Finished compost** can be made at home, purchased at garden supply stores, or found at composting facilities. To learn how to make your own, contact your loc organic-gardening club or read a composting book. Finished compost is the best mulch for vegetable gardens.

- **Aged manure** is often free from livestock stables. Make sure it is sufficiently aged and composted so it won't burn your plants or smell like the fresh stuff. If you wa your manure poison-free, avoid suppliers who spray insecticides at their sites to discourage flies. To avoid propagating Bermuda grass (*Cynodon dactylon*) or field bindweed (*Convolvulus arvensis*), avoid manure originating from animals that eat feed containing these two plants. Politely ask livestock owners and commercial suppliers about their product and they'll tell you what you need to know. Aged manure is a good nitrogen-rich material to bring fertility back to disturbed sites.

Place the manure as the bottom layer of mulch and carbon-rich tree bark or woo chips above as the top layer.

- **Tree bark and woodchips** can often be obtained free from local firewood distributors who consider them waste products, municipal dumps in well-woode areas, or tree-trimming companies, particularly those that cut trees from conflicti power lines for the local power company. Flag down the driver of the tree-trimmi truck, and give him or her a map to your site and where you want their chipped trimmings dumped (saving them a trip to the more-distant dump) (fig 7.5). Mak your own mulch by renting a heavy-duty chipper for a day when you can mulch the accumulated prunings from your site and your neighbors'. Since the bark and chips are generally bigger and heavier than manure and compost particles, they w well as an anchoring top layer—especially in areas of strong winds. Two inches (5 cm) of aged manure or compost topped with 2 inches (5 cm) of dry tree bark or wood chips is my favorite combination.

Fig. 7.5. Free mulch delivered!

Woodchip mulch is great beneath woody plants such as trees and shrubs; and on driveways where the wheels can help break down the material.

- **Straw** can frequently be obtained free at the conclusion of straw-bale wall raising Water-damaged or broken bales are available from feed stores for close to nothing After spreading straw over the soil, spray it with water to compress and lock it int itself, reducing the chance of it blowing away. Straw makes a good general mulch use in vegetable gardens, but it will need seasonal reapplications due its rapid decomposition.

- **Discarded paper products** such as cardboard, newspaper, junk mail, and office paper can all be mulch, and will eventually decompose into soil. Remove staples t reduce hazards. Cover these materials with straw, manure, compost, fallen leaves, bark so your landscape looks fertile rather than trashy. By covering paper product you'll also keep them from blowing away.

- **Discarded natural fibers** such as old cotton clothing, wool rugs, and damaged basketry can also be used as mulch since they will eventually break down into the soil. Again, cover them with straw, compost, or bark for a cleaner appearance.

- **Grass clippings** can be recycled right back into your lawn. Called *grasscycling*, th a faster, cheaper, and easier way to maintain a healthy lawn than conventional management that tosses grass clippings into the garbage. See the resources in appendix 4 for more information.

- **Fallen leaves** decompose into fertile soil that produces more plants that produce more leaves that decompose, contributing to the next mulch layer. Assist this nat cycle by raking or sweeping fallen leaves toward your plants. Consider bagged lea sitting on street curbs as gift-wrapped mulch to take home and use.

- **Prunings** from your plants smaller than 3/4 inch (1.8 cm) in diameter should be up to about 4-inch (10-cm) or shorter pieces and laid beneath the plants from wh they came. All plant parts work as mulch, so help your plants mulch themselves (7.6B,C).

Fig. 7.6A. Before. Compact, bare soil

Fig. 7.6B. Capturing leaf drop and cut-up prunings in water-harvesting basin.

Fig. 7.6C. After. Sponge-like, fertile soil

- **Vegetation** is the "living mulch" that shelters soil, moderates temperature, and creates beneficial micro-climates for more vegetation. Desert trees tend to grow w their branches draped down to the ground, where they shade the soil, protect the bark from sunburn, and create habitat for wildlife. Avoid the temptation to prun desert trees to create single tall trunks, and instead allow them to take on their natural, stronger, multi-trunked shape.

- **Rock and gravel** make long-lasting surface mulches that don't break down. Ligh colored gravel reflects sunlight and can cool the soil surface in hot climates, altho the air above the rock will still be hot. Dark-colored gravel absorbs, stores, and re radiates heat—often an advantage in colder climates. Rock and gravel can be use below grade for infiltration trenches, but while they encourage rapid infiltration water into the soil, they lack the water-holding capacity of organic matter used as vertical mulch.

Do not use decomposed granite where you want to infiltrate water, such as in basins, since the clay fines in the material can seal the surface. If decomposed granite is used, limit its use to raised pathways, accessways, and gathering areas.

If using the gravel as a surface mulch to cover a path, driveway, or gathering area, it must be both open-graded (aggregate particles of one size) for good porosity, and angular (not round) aggregate so the gravel interlocks into itself and stays in place, rather than rolling around like pea gravel does. Aggregate larger than 3/8 inch (9 mm) makes walking or rolling a wheelchair or baby carriage difficult. (See the discussion of porous aggregate in chapter 8 for more.) Rock and gravel are not used for vertical mulches because they lack the water-holding capacity of organic matter.

- **Sand** is a mulch traditionally used on lands farmed by Native Americans such as Hopi and Navajo, where it naturally overlays clay soils. Dry-farmed gardens are planted by temporarily moving a section of sand aside to expose a small area of n clayey soil below. The clay is punctured using a digging stick, a few seeds are dropped in, the hole is covered with moist clay, then sand is put back over the cla soil. Corn varieties domesticated by the Hopi and Navajo then germinate and can grow through over a foot of soil and sand mulch.

MULCH LAYERING

Different mulch materials often work together, sometimes with two or more materials working better than one.

You can layer mulch by topping unaesthetic organic mulch materials, such as newspapers, junk mail, and old cotton rags, with your tree bark or shredded straw mulch. Lightweight materials that can blow away can be topped with some aged manure or compost, then topped with bark. Junk mail and the high-carbon trashy stuff has little nutrient value, but as it decomposes it will provide the spongy blanket effect so important in drylands for absorbing water and slowing its loss to evaporation. Note: I apply thicker layered mulch only within earthworks harvesting additional runoff and/or greywater. The added moisture then enables the beneficial decomposition of the mulch. See fig. 7.7 of layered mulches in an infiltration basin.

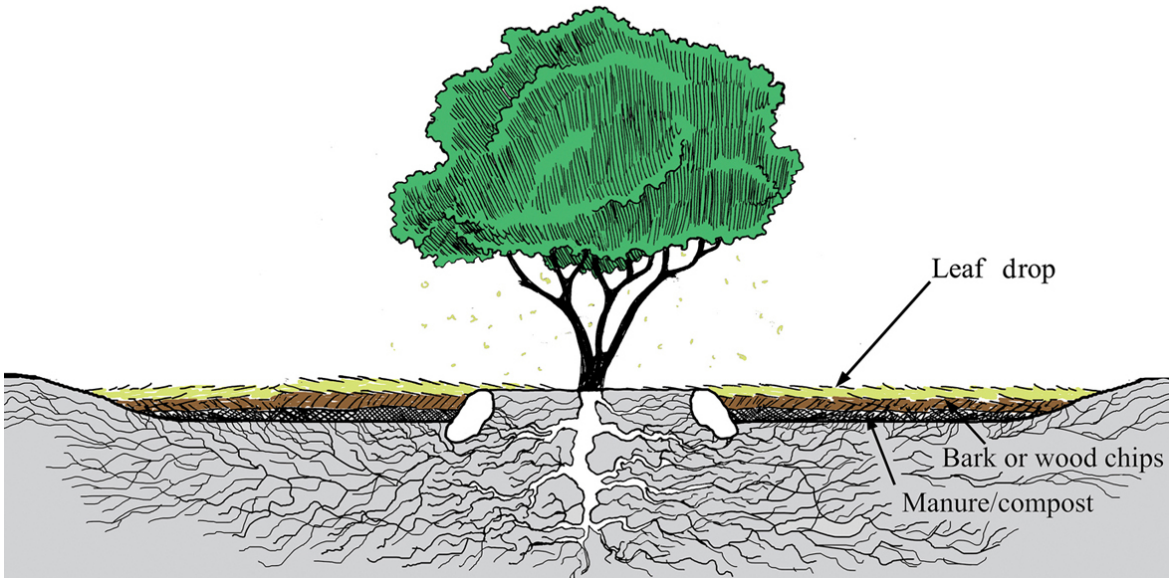


Fig. 7.7. Layered mulch: manure or compost on the bottom for nitrogen-rich fertility, straw, wood chips or bark above as a top dressing, covered by accumulated leaf drop and cut-up prunings as the self-regenerating mulch material

My favorite layered mix is to to place the more nitrogen-rich compost or aged manure on the bottom, then big carbon-rich stuff like bark on top, since this mix provides a nutrient boost from the compost and aged manure, and an insulative spongy blanket of the coarser mulch. But when available materials call for heavier, nitrogen-rich materials to be layered atop lighter, carbon-rich materials that can work too. And on top of any layered mulch goes the leaf litter naturally falling from above.

IMPLEMENTATION STEPS

SITING

To determine the feasibility and type of mulch, consider the slope and condition of your site's watershed. Significant runoff will wash mulch away, so mulch is nearly always used in combination with other water-harvesting earthworks and placed within their anchoring depressions. However, if ample materials exist, mulch can also be applied between earthworks, or atop raised earthen pathways, or on berms where it slows erosion (figs. 7.8A, B).

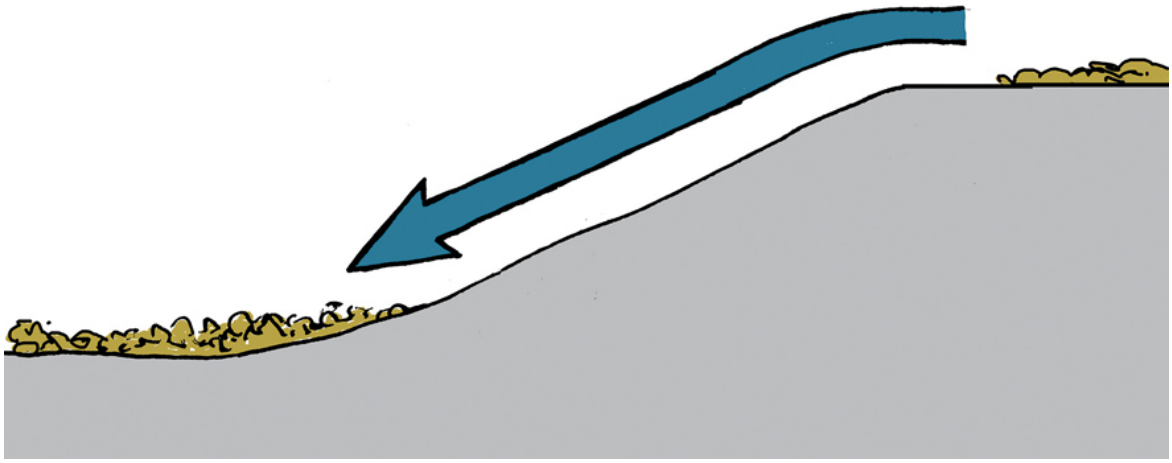


Fig. 7.8A. Unanchored mulch washed off slope. Arrow denotes unchecked runoff.

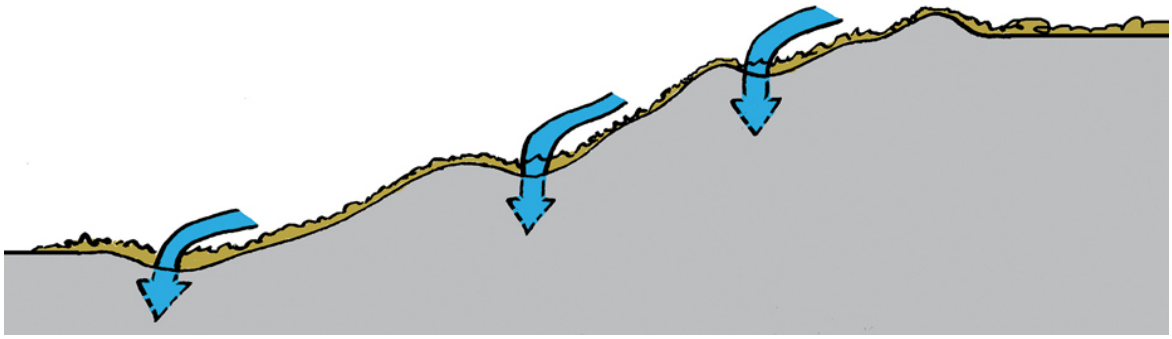


Fig. 7.8B. Mulch anchored within basins of earthworks where runoff has been checked. Arrows denote runoff infiltrated into the soil.

Mulching can be widely used on small lots, since the amount of material needed to cover the area is relatively low. Be more selective in its use on larger sites to keep material needs from getting out of hand. For example, you might apply mulch only to lush areas and earthworks around buildings and within gardens, while leaving hardier vegetation and more-remote earthworks to provide their own mulch.

In fire-prone areas, use organic mulch only in depressions around vegetation where moisture lingers; this mulch can help make plants more resilient in droughts. Keep organic mulch light right around buildings, and break up your property with organic-mulch-free firebreaks of rock and gravel mulch, raised paths, or wide berms.

PLACING AND THICKNESS OF MULCH

I only apply mulch as deep as can be fully saturated in a good storm, so a thicker layer of mulch works well where the basin harvests greywater or additional runoff such as from a roof's downspout or a patio, where enhanced infiltration is a greater

need. However, a thinner layer of mulch works better where the basin receives only direct rainfall, and you don't want the mulch to prevent water from a light rain from reaching the soil. A thicker mulch also makes deeper basins appear shallower—a good thing beside paths and patios where you may want the greater water-holding capacity of a deeper basin, along with a shallower, gradual, and safer topography. But *never apply mulch to a level above an earthwork's stormwater inlet elevation*—you want to receive that water, not divert it away.

In dryland climates I find an initial application of a 4-inch (10-cm) thickness of *organic* mulch to be optimum within earthworks receiving runoff and/or greywater. But I use only an initial 2-inch (5-cm) maximum thickness of mulch in areas receiving only direct rainfall. Less mulch breaks down too quickly and weeds are more likely to grow up through it. Thicker applications may reduce rather than increase soil moisture by soaking up all the water from a light rain, and leaving the soil below dry. However, it's fine if naturally occurring mulch exceeds 2 inches (5 cm)—the build-up is not too sudden, and roots grow through it.

That initial layer of organic mulch will likely decompose to half its thickness or less in a few months. Whether I rebuild the mulch depends on how much water the mulched area receives. For areas that get only direct rainfall, I typically let the mulch decompose, while encouraging the natural accumulation of leaf-drop. For areas that receive direct rainfall, plus additional water as runoff, greywater, or supplemental irrigation with well/municipal water, I add mulch to maintain at least a 2-inch (5-cm) thickness until leaf-drop from the plants does it for me. The additional water ensures the moisture will reach the soil, and the thicker mulch enables the area to more quickly absorb the water.

Mulch the entire basins of water-harvesting earthworks, but use only a very thin layer or no mulch within 6 inches (15 cm) of the trunks of plants; here limit organic mulch depth to 1/2 inch (13 mm). This ensures you don't retain moisture against the above-ground portions of the plant that might induce rot or diseases or attract insects (box 7.2, figs 7.9A, B).

Box 7.2. Mulch in the Vegetable Garden

Three to four inches (7.5–10 cm) of mulch seems ideal for my southern Arizona vegetable garden—but not right around seedlings. Mulch creates a moist and fertile microclimate atop the soil, so it attracts a number of beneficial burrowing insects and worms that eat decomposing organic matter and turn it into still more fertile soil. Most don't bother live plants, but some, such as sow and pill bugs, eat very small plants or seedlings. Therefore, I spread vegetable seeds and transplant seedlings in 4- to 6-inch (10–15 cm) wide rows of temporarily bare earth, then lay mulch between the rows. This way the mulch reduces some evaporation of soil moisture, sow and pill bugs stay under the mulch, and seedlings are not

eaten (fig. 7.9A). When plants reach 8 inches (20 cm) in height the threat of being eaten is gone. I then spread the mulch right up to the base of annual plants and throughout the garden up to a depth of 3 to 4 inches (fig 7.9B). However, see what works in your area and climate by experimenting. In the wetter climate of upstate New York, mulch against lettuce can create a slug-fest.

With the mulch now in place, I can reduce watering by about 25%, or even more if I irrigate under the mulch (the soil then absorbs most of the water directly, rather than the mulch absorbing it first). As a bonus, the mulch dramatically suppresses weed growth.

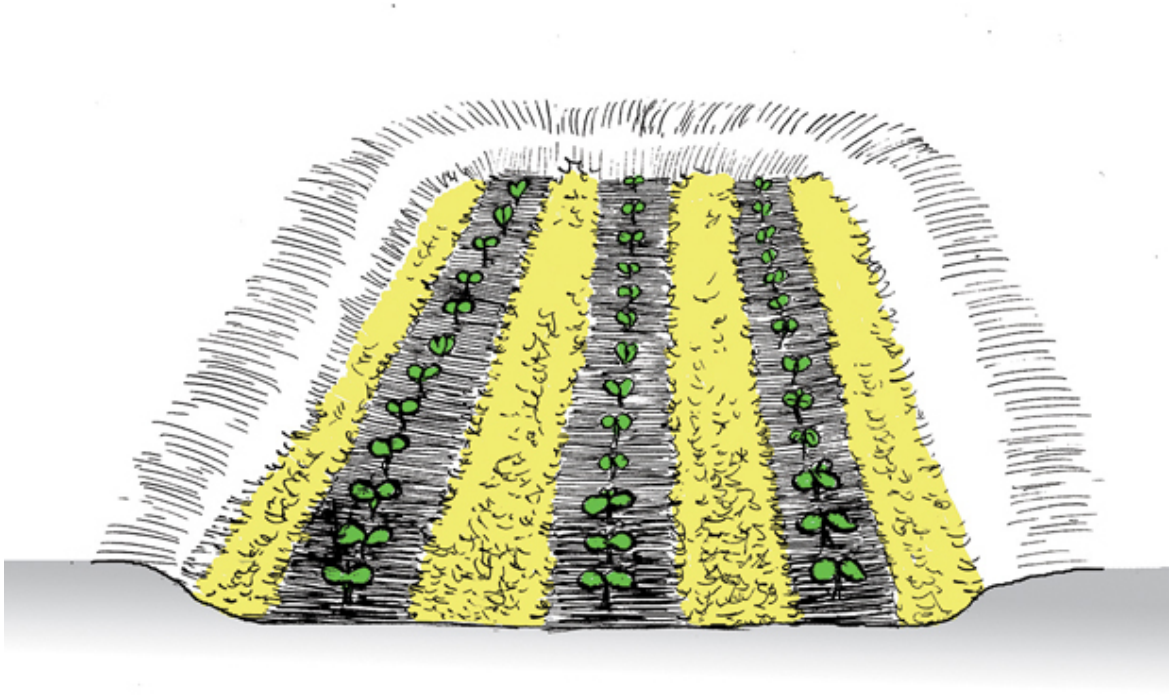


Fig. 7.9A. Mulching with straw between seedlings

Fig. 7.9B. Mulched garden with mature vegetables

Thicker organic mulch can be used in areas with greater concentrations of water and wetter climates. Ruth Stout, the Connecticut "Queen of Mulch Gardening" and author of *How to Have a Green Thumb without an Aching Back*, found that in her climate you need a minimum of 8 inches (20 cm) to keep weeds at bay. She calculated that 25 50-pound (22 kg) straw bales would be needed to cover a 50- × 50-foot (15- × 15-m) space with 8 inches (20 cm) of straw.[2]

A gravel mulch should not exceed 2 inches (5 cm) in depth when used around plantings, but if used as a porous paving material on paths or driveways it can be as deep as 6 inches (15 cm) (see chapter 8). In areas where you are trying to establish wildflowers, use a very light layer of gravel or decomposed granite mulch no thicker than 1 inch (2.5 cm) to help anchor seeds and provide tiny microclimates of moisture, but avoid using organic mulch. Many wildflowers are pioneer species that prefer barren, disturbed soils.

In wet or fire-prone areas keep organic mulch 5 feet (1.5 m) away from a building's foundation to avoid excessive moisture buildup in wet times and the accumulation of fire-prone material in dry times.

APPLICATION AND DRESSING UP OF MULCH

I'm a laid-back gardener and allow my mulch to have a wild, natural appearance. I'm also thrifty and love turning "wastes" into resources, so I use materials that are

on hand or can be freely salvaged. I spread mulch to the desired thickness on the surface of the soil and that's it. However, if you want a more manicured appearance you can spend a little more time and money to get the look you want. Uniformly screened mulches are available for purchase from local composting facilities, landscaping companies, or garden-supply stores. You can get the same result with salvaged materials if you do the screening or processing yourself. For example, straw run through a chipper/shredder comes out in fairly uniform pieces 2 inches (5-cm) long or shorter, while manure ground up with a rototiller turns cow patties and dung balls into a fluffy top dressing.

MULCH, DRAINAGE, AND OVERFLOW SPILLWAYS

Mulch should mimic the drainage pattern of the soil it covers so apply it evenly over the general landscape to maintain the existing drainage pattern. If you need to change the drainage pattern, regrade the underlying soil prior to mulching.

Within water-harvesting earthworks, cover the surface of basins and depressions, while keeping the spillway clear to allow the unhindered outflow of excess water.

MULCH AND PLANTS

Vegetation is the key to getting your water-harvesting earthworks to regenerate their own mulch. If you are planting from seed, do not apply more than a sparse 1/4-inch (0.6-cm) thick layer of mulch or you will hamper germination. Once your plants have grown taller than 6 to 8 inches (15–20 cm), you can apply a thicker layer of mulch.

But desert plants that are prone to rot, such as cacti, should *not* be mulched with organic material that will hold moisture around the base of the plant These plants are typically not planted in basins where more water gathers and organic mulches work best. Instead these plants are typically placed outside of basins where there is better drainage; gravel and rock mulches work fine around the cacti.

For more information on mulch and plants, see chapter 11 on vegetation.

MAINTENANCE

Check your mulch periodically, especially during or just after big rains, and replenish it as needed. To recharge nutrients, place compost or aged manure on top of the old mulch, then place straw, bark, or wood-chips on top of it all. Using this layered strategy, as the carbon-rich mulch breaks down it utilizes nutrients from the compost or manure rather than the soil. As decomposition continues, nutrients are slowly time-released into the soil.

Let mulch naturally accumulate in your earthworks; this is often the only mulch replenishment/recharge needed. Rake in leaves from nearby patios. Cut prunings that are smaller than 3/4-inch (1.8-cm) diameter into 4-inch (10-cm) or shorter sections, and drop them under the plants from which they came. Larger diameter prunings make good firewood.

VARIATION OF MULCHING

VERTICAL MULCHING

Vertical mulching is the technique of filling holes or trenches with porous organic matter, without mixing mulch *into* the soil or covering the holes with dirt. Vertical mulching creates spongy conduits leading water quickly down to the root zones of adjoining plants where the moisture is released over an extended period of time (fig. 7.10). Holes or trenches should be constructed 6 to 18 inches (15–45 cm) away from the base of newly planted trees, 12 to 15 inches (30–38 cm) deep, and 1 to 2 feet (0.3–0.6 m) wide. Trenches can range from 2 to 20 feet (0.6 - 6 m) long, with the longer trenches used when you have a lot of mulch material to dispose of and localized runoff you want to harvest. The trench is always laid on contour.

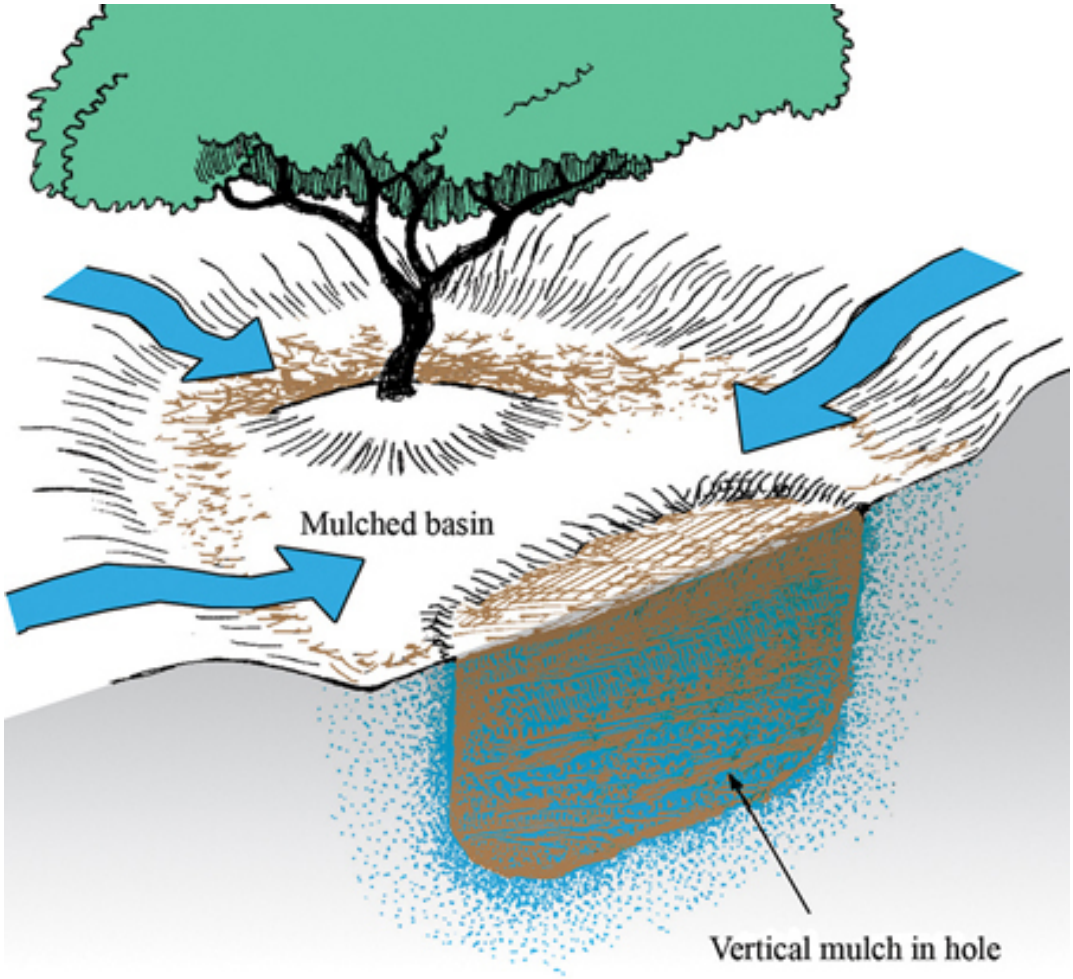


Fig. 7.10. Vertical mulch variation (mulch-filled hole or trench) encouraging infiltration and retention of water deeper into the root zone of the soil

David Cleveland and Daniela Soleri report in *Food from Dryland Gardens* that "In semiarid India vertical mulch of sorghum stubble in trenches 12 inches (30 cm) deep and 6.5 feet (2 m) apart gave 25 times more grain yield and 2 times more straw yield than the areas without vertical mulches in a very dry year."[3]

MULCHING AS MORE THAN A WATER-HARVESTING STRATEGY

MULCH FOR DELINEATING PATHS, PATIOS, AND PLANTINGS

A change in surface materials can be used to delineate different areas of a site. Well-mulched surfaces clearly distinguish planting areas and gardens from patios and earthen paths, and can prevent people and animals from mistakenly disturbing

these "green areas." If by accident someone does walk into a planted area, the mulch helps protect the surface and reduce soil compaction.

MULCH FOR STABILIZING CAMPSITES

Sleeping on cold bare ground will suck the heat out of your body and make your hips and shoulders ache. Camp on that bare spot repeatedly, and you'll hasten erosion. However, if you sleep on a thick bed of mulch, you'll be insulated from the cold ground and padded from pain. The mulch can help curtail erosion too. Outfitters, outdoor enthusiasts, and camp managers can make a positive impact on people and environment by mulching their campsites. Large-sized organic mulch, like bark and woodchips, works well on paths where feet will slowly break it down, while finer mulches like straw, pine needles, or fallen broad-leaves work well in sleeping areas over which tents are set up or sleeping bags laid down. Earthworks such as terraces can create level sleeping areas, hold mulch in place, improve rainfall infiltration into the soil, and encourage the growth of the surrounding vegetation that regenerates the mulch, stabilizes the soil, and makes for beautiful surroundings.

For fire safety, keep organic mulch away from campfires.

MULCH AS WEED CONTROL

Mulch retards weed growth if it is spread at least 4 inches (10 cm) deep. Bare, disturbed earth attracts the germination and growth of "pioneer species." These tough plants with a preference for disturbed soil anchor and protect the exposed soil, but too often these days many of these pioneers turn out to be nonnative invasive plants that are detrimental to native-plant and animal communities. If thick mulch covers the soil, the establishment of seeds of all kinds is reduced.

Likewise, I've found mulch reduces troublesome Bermuda grass (*Cynodon dactylon*) or large crabgrass (*Digitaria sanguinalis*). Cover this grass with 2 to 3 inches (5–7.5 cm) of manure (fresh or "hot" manure is best since it burns the grass). Next, lay down large pieces of cardboard with edges overlapped 18 inches to 2 feet (45–60 cm) so the grass is deprived of sunlight. Bicycle or furniture boxes with staples removed are best since they are large and freely available from dumpsters. Then, spread 2 to 4 inches (5-10 cm) of topsoil, aged manure, or compost over the cardboard to hold everything down. Finish with an appealing top-dressing of mulch, such as straw or salvaged bark. The Bermuda grass dies out when it no longer receives energy from the sun. As it decomposes it too becomes mulch and improves the soil—Bermuda grass as a soil builder! The cardboard breaks down in a year or two, but by then the Bermuda is soil.

This method works with an isolated patch of Bermuda grass, if you cover it all and *promptly* pull the few shoots that will grow through or around it to reach daylight. In cases where Bermuda is invading your yard from your neighbor's yard and you can cover only part of the patch, it is much less effective and the grass will eventually come back. Still, this method will improve soil, conserve water, and at least slow the spread of the Bermuda grass. Rolls of recycled cardboard can be purchased for mulching large areas.

You can also employ some friendly, manure-producing animals. Both chickens and desert tortoises eat Bermuda grass. I located my chicken run on a pasture of Bermuda; within months all the grass was gone (fig. 7.11).

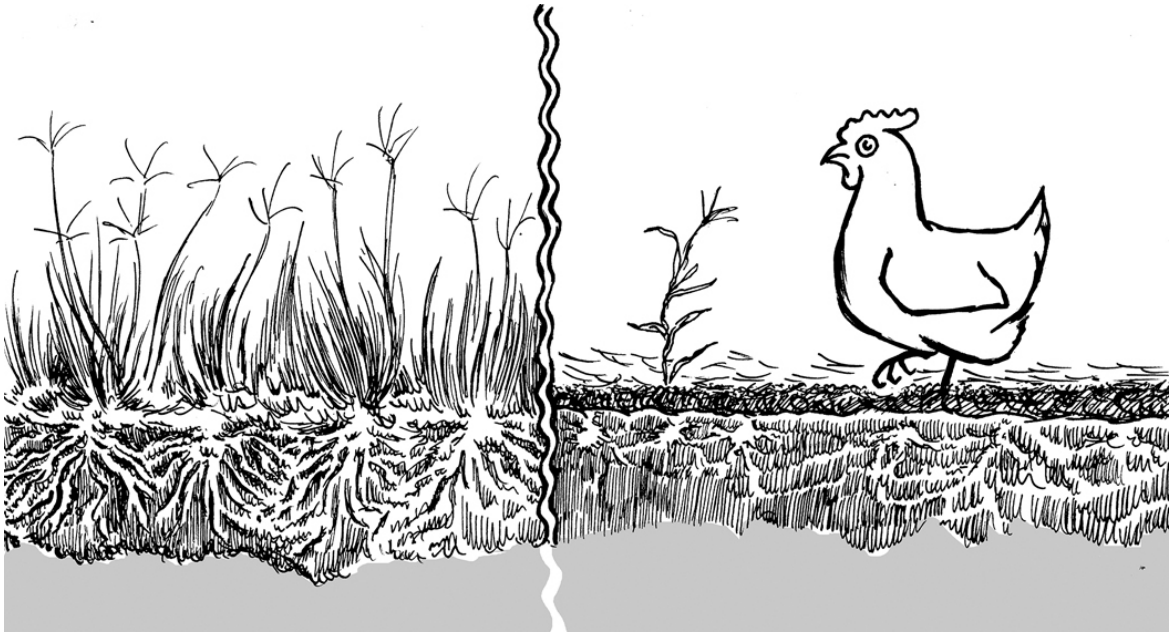


Fig. 7.11. Rampant Bermuda grass versus grass hunted and eaten

MULCH AS A MULTIPURPOSE DEODORIZER FOR LIVESTOCK PENS

I keep a 4-inch (10-cm) layer of dry straw and wood chips spread over my backyard chicken run and the floor of my chicken coop. This eliminates odors from chicken droppings and greatly improves the drought-tolerance and health of the dense, chicken-friendly vegetation planted throughout. Odors are eliminated through an aerobic decomposition process. The beneficial microorganisms that make this happen need a carbon source (dead plant material), a nitrogen source (fresh manure, urine), moisture, and oxygen to grow and multiply.

In my chicken run, carbon-rich mulch counterbalances the nitrogen-rich droppings from the birds. With too little nitrogen, decomposition slows down. With too much nitrogen, the excess is released as a smelly ammonia gas.[4] I don't mind decomposition taking a while but I do mind bad odors, so I go heavy on the organic mulch. That leaves my chicken yard smellin' pretty.

In addition, all this mulch and manure fertilizes the soil, increasing soil moisture and soil life, thereby providing the chickens with more food in the form of many more earthworms and beneficial insects, which the birds love to scratch up and eat. The healthier soil also benefits forage-producing plants located in and around the pen. Indigenous plants with berries and leaves consumed by poultry include wolfberry (*Lycium* spp.) and desert hackberry (*Celtis spinosa*), which are mixed with edible cacti, barberry (*Berberis trifoliolata*), pomegranate (*Punica granatum*), quailbush (*Atriplex lentiformis*), and others.

MULCH AS A MULTIPURPOSE DEODORIZER FOR FRUIT-TREE URINALS

Just as carbon-rich mulch counters the odor of livestock urine, it does the same for human urine. I've been to numerous gatherings where screened mulch beds are temporarily set up to give men and women the option of using a safe, effective, waterless urinal. The beds conserve a tremendous amount of water compared to flush toilets—which can use 1 to 8 gallons (3.8–30 liters) per flush—and greatly reduce the strain on septic systems (fig. 7.12).

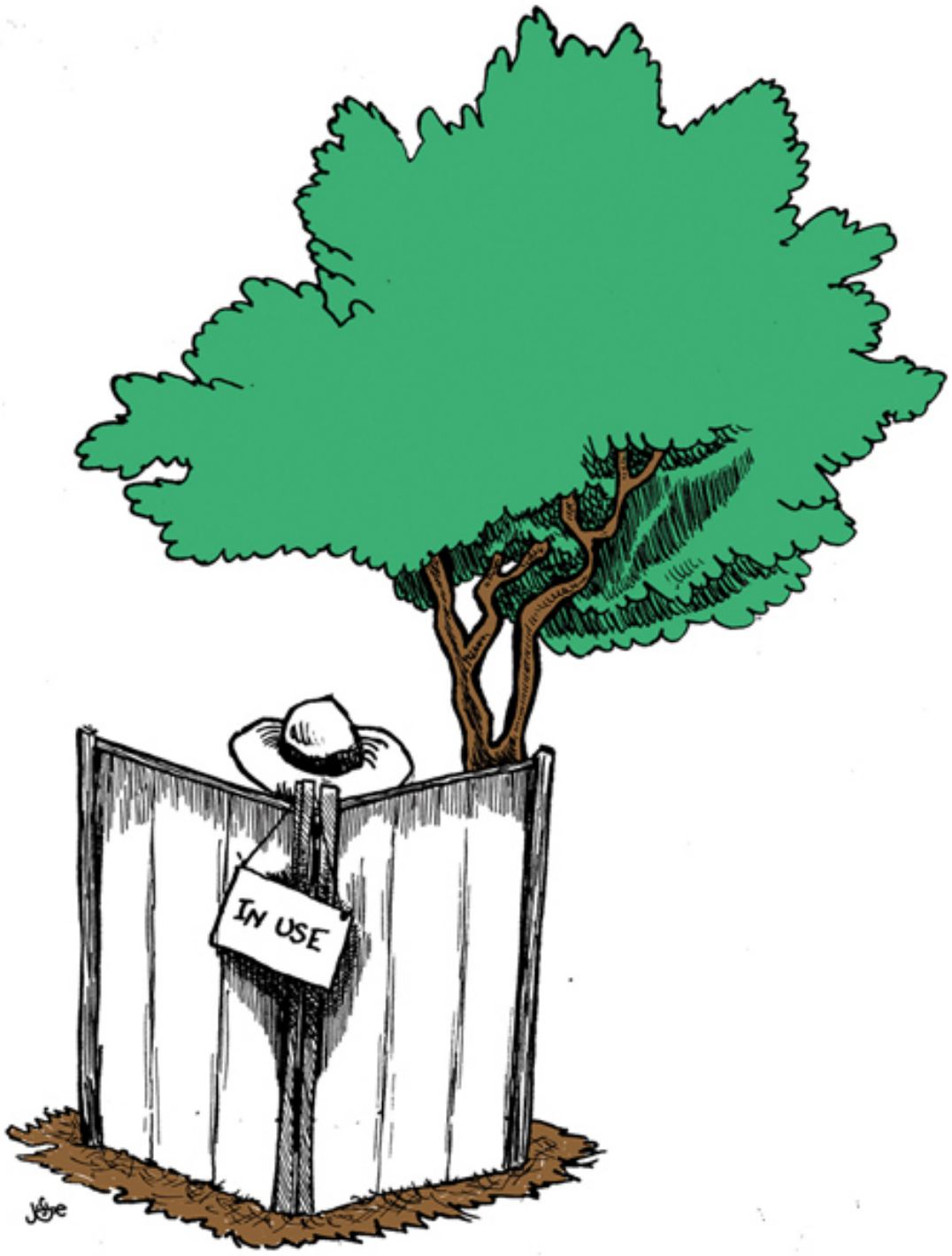


Fig. 7.12. Fruit-tree urinal

A temporary privacy screen is erected beside a fruit or native tree located away from any water sources into which urine might accidentally drain. Behind the screen, a thick bed (8 inches [20 cm] or more) of dry high-carbon mulch, such as straw, sawdust, or wood-chips, is laid down. People then urinate directly on the

mulch. Stepping blocks are set up for women. There are no bad odors, and the tree gets a dose of nitrogen oxidized by the mulch. If odors arise, that is a sign for maintenance. More dry mulch must be added, or the urinal is moved to another mulch bed beside another tree. The urine beds are relocated every two days or so at large gatherings (over 150 people). Used mulch either stays with the original tree as is, or is mixed into a compost pile for further decomposition before it is returned to the tree. Ideally, the urine beds are located in water-harvesting infiltration basins where concentrated salt-free rainwater can dilute the salts introduced by the urine.

Folks get so excited by this simple system that many set up their own, saving water and generating fertilizer at home. As Swedish university studies found, one adult produces enough fertilizer in urine to grow 50 to 100% of the food required by an adult.[5]

A mulched urinal must be well managed to keep it odorless. While urine is usually sterile in healthy populations,[6] it can act as a vector for some diseases and parasites such as typhoid and schistosomiasis.[7]

For more resources on using urine in gardens and information on composting toilets see the resources listed in appendix 4.

MULCH AS A GARDEN AND SOIL AMENDMENT

Organic matter from many different local sources is a high-quality, low-cost resource for maintaining dryland garden soil fertility. It provides the following benefits to garden soils as it decomposes to humus:

According to the comprehensive guide, *Food from Dryland Gardens*,

- Organic matter is the source of 90–95% of soil nitrogen, including that which cycled through microorganisms.
- When organic matter makes up more than 2% of soil, it can be the major sourc available phosphorus and sulfur.
- Organic matter is a major source of the cements necessary for aggregate formati create strong soil structure with a higher proportion of larger pores, which impı water-holding capacity and water and air movement.
- Organic matter may supply 30–70% of the negatively charged [ion] sites that h nutrient cations that plants can use. This electrical property also gives organic n the ability to act as a *buffering agent*, moderating the tendency of the soil to cha pH when acid or alkaline substances are added to the soil.

- Organic matter acts as a chelate: it forms compounds with metal nutrients (usu iron, zinc, copper, or manganese), increasing their solubility and availability to plants.
- Organic matter supplies carbon for energy to many soil microorganisms that perform beneficial functions such as nitrogen fixation.
- In cities where garden soils contain lead from exhaust fumes of vehicles or lead-paints, soils containing 25% or more organic matter significantly reduce the up of the poisonous lead by garden crops.
- Organic matter acts as mulch on the soil surface.[8]

ORGANIC MATTER MULCH SUPERIOR TO ROCK/GRAVEL MULCH FOR SOIL MOISTURE, CARBON SEQUESTRATION, AND MORE

Research by Mitch Pavao Zuckerman and C. Sookhdeo found that in the semi-arid community of Tucson, Arizona, vegetated street-side infiltration basins harvesting street runoff mulched with organic material had *twice as much soil moisture* and twice as much soil organic matter as such basins mulched with rock, despite there being smaller areas of impervious catchment draining into the organically-mulched basins in the study.[9]

Soil organic matter consists of fresh and partially decomposed plant and animal residues, the living biomass of soil microorganisms, and humus: the well-decomposed organic material.[10] As soil organic matter (SOM) levels increase, so does the soil's ability to sequester more climate-changing carbon from the atmosphere, as the SOM is typically estimated to contain 58% carbon.[11] Additionally, SOM helps bioremediate or filter pollutants.

REAL-LIFE EXAMPLES OF MULCHING

ANCIENT HOHOKAM ROCK MULCHING—SOUTHERN ARIZONA

Throughout southern Arizona one can find remains of cultivated plots of agave, a major food and fiber plant among the Hohokam. The Hohokam lived here before A.D. 1400 and knew the value of mulch. They piled a mulch of rocks around the bases of their cultivated agave plants. Remains of these piles can still be found today,

less than 29 inches (75 cm) high, and averaging about 1.6 yards (1.5 m) in diameter.

A study by Suzanne and Paul Fish, Charles Miksicek, and John Madsen entitled "Prehistoric Agave Cultivation in Southern Arizona" reports that vegetation today usually favors the microclimates of the rock piles over adjacent non-mulched areas.[12] Excavations found root biomass directly beneath the rock piles averages 2.7 times the weight of roots in adjacent unmulched areas. The plants were most likely responding to greater soil moisture below the piles and nutrients from organic matter caught between the rocks.

During the same study, an experimental planting of agaves in prehistoric Tucson fields revealed additional benefits from rock mulch. During dry months, rodents damaged agaves planted without rock mulch as they searched for food. Agaves in rock piles were left untouched.

Within the 135-square-mile (350-km^2) study area northwest of Tucson, the researchers discovered numerous rock pile fields—including over 1.9 square miles (5 km^2) of fields in the upper bajada section alone. Within this latter section, there are an estimated 42,000 rock piles and 1,173,000 linear feet (360,000 m) of terraces and check dams harvesting water and soil. Utilizing these numbers they calculated that the agave harvest could support the caloric requirements of 155 people each year, while producing an additional crop of 4.1 tons (3.72 metric-tons) of fiber.

Using rock mulch, terraces, check dams, and appropriate crops, the Hohokam maintained a productive system of agriculture that depended entirely on harvested rainfall. The downside may have been the large amount of wood needed to roast and process the harvested agave, resulting in severe deforestation of the area that may have made the local climate drier— but we'll leave that for another discussion.

JUNK MAIL AS PRODUCTIVE VERTICAL MULCH—ALBUQUERQUE, NEW MEXICO

Whenever Chris Meuli plants a tree on his land in the high plains east of Albuquerque, New Mexico, he digs a hole and a trench. The hole is for the tree and the trench is for a junk mail sponge (fig. 7.13A, B , C).

Fig. 7.13A. Newly planted tree beside hole for junk mail. Soil from hole used to make downhill bommerang berm left of tree

Fig. 7.13B. Tree with adjacent hole filled with phone books, magazines, and junk mail

Fig. 7.13C. Junk mail topped with pretty straw. Straw is packed down in place to prevent it from blowing away. Roots of adjacent tree will tap the moisture held in the junk mail mulch.

Like most desert soils, those on Chris' site have an organic matter content of only 1 to 1.5%, and store significant water for only a few days after a rainfall. So Chris packs 2 to 6 cubic feet (0.05–0.16 cubic meters) of junk mail and other organic matter into the trench next to the new tree. Everything he has on hand is thrown in whole. Chipping and shredding are jobs left to the termites and earthworms. Any biodegradable matter that absorbs water, such as straw, newspaper, phone books, or old love letters, can be used as a "mulch sponge." Though Chris stops adding carbon sponge material 3-4 inches (7-10 cm) from the top of the hole because it will expand 15% or more when wet and can actually rise up out of the hole, wicking moisture out of the hole in our dry winds. As for concerns about potential heavy metals emanating from the inks used on junk mail, Chris feels the amounts are minuscule and are quickly diluted in a sea of humus, virtually inactivating them. Just to be safe he avoids using junk mail around edible root crops.

"Junk mail is not attractive," admits Chris, "so I always mulch over it with a thick layer of straw (expensive!), grass clippings (free!), or leaves (free!). Each fall I harvest leaves off of the sidewalks of Albuquerque, which are otherwise destined for the dump, and carry them out to Edgewood. I try to never drive empty. I'm able to collect between 500 and 800 bags every year!"

Chris constructs his mulch sponges on contour, 12 inches (30 cm) to 14 inches (35 cm) wide (standard newspaper width) and 4 to 20 feet (1.2 - 6 m) long on contour. He digs them only 12 to 15 inches (30–38 cm) deep since ample tree roots live in this upper layer. He positions these sponge trenches 6 to 10 inches (15–25 cm) away from his tree holes with undisturbed dirt in between (refer to fig. 7.10, illustration of vertical mulch).

The sponge should be sited to collect enough runoff to thoroughly saturate it once a season, or at least once a year. So, Chris deposits the soil dug from the trenches downslope to create berms to help slow runoff and direct it around the newly planted trees and into the mulch trenches. If enough time and energy are available, he extends the berms into a more expansive series of boomerang berms to guide even more runoff to the trees and sponges.

Once a tree is planted, and the adjoining trench is full of mulch, the berm is complete, and a thick layer of mulch is spread over the basin, Chris gives the tree a deep watering. If it has been particularly dry he will also fill the sponge with water. This will be the only time he ever waters the tree or the sponge.

The sponges absorb enough moisture from winter snows to maintain the trees until the July rains, which sustain them until the following winter. The sponges are moisture banks providing a very slow release of water over a long period. After months of drought, Chris has dug his hands deep into the mulch to find the junk mail moist to the touch. Mats of native tree and native grass roots invade the sponges for this moisture.

After years of monitoring, the plants beside the sponges have never shown any signs of nitrogen deficiency (chlorosis), despite the high carbon content of the sponge's mulch. Ecologist friends Jim Brooks and Scott Jackson have found the same results in sandy soil sites around Albuquerque, receiving about 8 inches (203 mm) of rain a year at its 5,000 foot (1,500-m) elevation.

Chris has planted hundreds of trees this way, creating about 300 mulch sponges within the alkaline clay soils of his 8-acre (3.2-ha) site, where rainfall averages 14 to 16 inches (355–406 mm) per year at an elevation of 6,700 feet (2,042 m). The sponges are scattered amidst additional earthworks such as five long earthen contour berms, dozens of smaller earthen contour berms, over a hundred boomerang and

contour berms made of brush and prunings, and about a dozen small check dams in the drainages.

His earthworks are his irrigation system. Chris relates, "On my land I have well over a mile and a half (2.4 km) of drip irrigation, laid in the mid-1980s. It was way too expensive, took a lot of time to maintain, and delivered very hard aquifer water to the trees. I no longer use any of it! The trees grow much better with the sponges, probably for a variety of reasons, including the clean rain water, more organic matter nearby with more worms and soil life, and less interference from gophers and ground squirrels who seemed attracted to the underground moisture plumes created by the drip systems."

The mulch sponges are not permanent. After four to five years they decompose into a rich porous soil, but by that time trees are well established and survive without sponges.

Over the past five years, Chris has made sponges from most of the newspapers, magazines, and cardboard "produced" from 5 to 10 households, which amounts to at least 3 to 5 tons (2,700–4,535 kg) of organic matter per year. Chris says, "It seems to have an amazing effect on the people who donate the materials to me; they seem much more aware of the amount of material they use in their lives and more thoughtful about where their 'waste products' end up. They really enjoy visiting the trees that have been nourished by their household wastes, discarded documents, and old love letters."

In the upper portion of his land, where there's a great view, Chris and friends planted three ponderosa pines of similar size in a burial ceremony for their dear friend Don Byrd, the man who originally introduced Chris to this place in the 1970s. The tree planted atop a sponge mixed with Don's ashes has soared, growing twice as fast as the other two.

MULCHING THINNED AND DEAD TREES ON CONTOUR—SANTA FE AND ALBUQUERQUE, NEW MEXICO

During successive years of drought in the pinyonjuniper forests of northern New Mexico, huge swaths of pines succumbed to an infestation of bark beetles. The standing dead trees that are left behind pose a serious fire threat. Interestingly, this fire threat, and potentially the bark beetle infestation itself, were exacerbated by over 100 years of fire suppression.

In the past, natural wildfires occurred every 5 to 15 years. These 300˚ to 400˚F (150-200˚C) fires prowled beneath the forest canopy in the high desert forest, burning grasses and culling small weak trees without harming tall mature trees. In

the absence of frequent moderate fires, small trees grow thick in the forest. Here they compete for nutrients and water, increasing the susceptibility of large trees to disease and creating fire ladders that feed raging fires (up to 2,000˚F or 1,100˚C), which kill young and old trees alike.

These problems became the solution using one of two strategies.

Strategy one: Thin young trees from the forest, cut down diseased trees, cover cut trees with clear plastic for six weeks to solar cook the beetles, then cut up and spread the treated wood over the landscape as brush sheet flow spreaders (figs. 10.32A,B).

Strategy two: Thin young trees and cut and chip dead trees for firewood and mulch. Dead trees can be cut anytime of year, but the resulting firewood must be covered in clear plastic for at least six weeks, tucking the plastic around the bottom of the wood pile with soil to create an airtight, solar-cooked bag of wood. Woodchips are spread to create raised mulched paths and contour berms, but only in winter when bark beetles are dormant (fig. 7.14A). This way the cambium of the woodchips, and its scent, dries out before temperatures rise in spring, and does not attract more bark beetles.

Fig. 7.14A. *Before*. Contour berms of woodchips. Chris Meuli's land, Edgewood, New Mexico. Credit: Chris Meuli Compare to fig. 7.14B

Fig. 7.14B. *After.* Abundant growth of new grasses above and below woodchip berms. Chris Meuli's land, 2006, post rains. Credit: Chris Meuli. Compare to fig. 7.14A

Chris Meuli finds woodchip berms to be the easiest and most useful water harvesting-strategy at his site. They require no digging and virtually disappear into the landscape as they mature, plus they hold back more water than brush sheet flow spreaders. At his 12-acre (4.8-ha) site east of Albuquerque, Chris has used over 70 cubic yards (53 m^3) of woodchips to create raised mud-free footpaths and over two dozen contour berms 10 inches (25 cm) high and 15 to 100 feet long (4.5–30 m). The woodchips were free, obtained from on-site thinning projects and municipal green "waste" mulching programs.

The effect has been wonderful. After receiving only 0.75 inch (19 mm) of precipitation over a seven-month period in 2005 to 2006, an incredible 17 inches (432 mm) of rain fell in summer 2006, including two 2.5-inch (63-mm) rainfall events. Even though the soil was already saturated, the mulch quickly swelled with rainfall and runoff, becoming dense and heavy and staying anchored in place.

Water collected behind the 10-inch (25-cm) berms before spilling evenly over 5- to 20-foot (1.5- to 6-m)-wide, level-topped sections of saturated wood-chips. Soil and nutrient-rich detritus collected behind the 10-inch berms to a quarter of their height. As Chris exclaimed, "I now have the densest stands of native blue grama grass growing above the berms that I've ever seen!" (fig. 7.14B).

Because Chris placed his two dozen woodchip berms close enough to one another to check runoff, beginning at the top of his slope, only two berms had overflow issues. Both had minor "washouts" less than a foot (0.3 m) wide and 2 inches (5 cm) deep, after which the wide dense berms became self-stabilizing. It took Chris less than a minute to repair the washouts by raking chips up onto the overflow area. To get ready for the next rainy season Chris will lay more woodchips atop the mature berms to bring their settled height of 6 inches (15 cm) back up to the original 10 inches (25 cm). Even without renewing the berms, the flush of newly established grasses would act as living, regenerative grass berms/sheet flow spreaders.

MULCHING IN WET LANDS—CONNECTICUT

Ruth Stout has passed on, but during her life she wrote many humorous and informative articles and books about her extensive use of mulch. At her Reddings, Connecticut, home (average annual rainfall of 51 inches or 1,295 mm) she raised abundant crops with no more than the rain falling directly onto her large garden—even in drought years. She called it "No Work Gardening." She planted the seeds,

mulched, and then came back later to harvest. No watering was needed due to soil-building and evaporation-reducing mulch, and very little weeding was needed since the mulch suppressed the weeds. It was so easy and she enjoyed it so much she still productively gardened this way at 100 years of age!

Check out some of Ruth Stout's books such as *Gardening Without Work* and *How to Have a Green Thumb without an Aching Back*.

Her video, "Ruth Stout's Garden," is a gem. See appendix 4 for more information on her books and videos.

CONCRETE *DRAINAGE*WAY TO COBBLE *INFILTRATION*WAY– TUCSON, ARIZONA

The Architecture building at the University of Arizona used to be bounded by a sterile, impervious concrete drainageway (fig. 7.15A), but life has now broken through. The concrete was jackhammered and turned to urbanite, or broken-up concrete chunks, then left in place to form a heavy cobble mulch. Heavy cobble is what you want in drainages where water flows through the earthwork rather than just settling into it. The cobble does not float away as organic mulch would.

A few native boulders and rocks were mixed in with the urbanite to improve and "naturalize" appearances. The result is a beautiful porous infiltrationway that slows, spreads, and sinks the flow of water like a natural cobbled waterway would (fig. 7.15B). Vibrant native trees and flowering shrubs now utilize that water. In fact, no city or potable water is needed to irrigate these established plants. Roof runoff and air conditioning condensate from the adjoining buildings are the primary irrigation sources.

This example of turning a drain into a sponge and the waste of jackhammered concrete into a resource of recycled cobble is my favorite part of this project, but it is only the overflow of a much larger potable-waterfree landscape – the Underwood Family Laboratory designed by Christy Ten Eyck at the new College of Architecture and Landscape Architecture building. A must-see when in Tucson.

See the Real-Life Examples section of chapter 12 for more on this site.

Fig. 7.15A. Before - *impervious* concrete *drainage*way. South of Architecture building, University of Arizona, Tucson, Arizona.

Fig. 7.15B. After - *porous* cobble *infiltration*way after the concrete was jackhammered and left in place. The infiltrating water passively irrigates the native vegetation growing through the cobble.

CHAPTER 8

Reducing Hardscape, Harvesting Its Runoff, and Creating Permeable Paving

Drying pavement creates solar ovens, while moist open soil grows solar-fed life.

Why reduce pavement and make it permeable? According to the Natural Resources Defense Council, "Worldwide, at least one-third of all developed urban land is devoted to roads, parking lots, and other motor vehicle infrastructure (fig. 8.1A). In the urban United States, the automobile consumes close to half the land area of cities; in Los Angeles the figure approaches two-thirds … Typical total imperviousness in medium-density, single-family home residential areas ranges from 25% to nearly 60%. Total imperviousness at strip malls or other commercial sites can approach 100%."[1] At what cost? When impervious cover reaches 10 to 20% of a watershed's area, ecological stress becomes apparent,[2] with pavement often making the effects of drought worse. For example, according to a report by American Rivers, the rapid expansion of paved-over and developed land in Atlanta, Georgia, and surrounding counties contributes to a yearly loss of rainwater infiltration ranging from 57 to 133 billion gallons. If managed on site, this rainwater—which could support annual household needs of 1.5 to 3.6 million people—would filter through the soil to recharge aquifers and increase underground flows to replenish rivers, streams, and lakes.[3] Watersheds are dehydrated as less water infiltrates into the soil and groundwater, and eroded as the volume and velocity of runoff increases, causing flooding and property damage (fig. 8.1B). The buildup of silt and pollution in waterways harms aquatic life and fishing, causes illness, and leads to shortages of drinking water.[4] And in the hot,

dry days between rains, exposed pavement and buildings store heat like a battery, then release it in the late afternoon and evening, raising temperatures by up to 10˚F (5.5˚C)—this is called the *heat-island effect*.[5]

Fig. 8.1A. Impervious landscape, a "sea of pavement" dehydrates the site and floods downstream areas.

Fig. 8.1B. Mountain Avenue as a river of runoff. Tucson, Arizona. Photo Credit: Ann Audrey

But—there's an alternative.

We can *reduce pavement* by creative planning and design, and where pavement remains we can consider the use of permeable paving instead of conventional impermeable pavement. *Permeable paving* is a broad term for water-harvesting techniques that use porous paving materials to enable water to pass through the pavement and infiltrate into soil. Permeable paving allows passive irrigation of adjoining plantings, decreases the need for expensive drainage infrastructure, and reduces soil compaction. The permeable paving allows roots to breathe, since it does not seal and close off the soil's surface and source of oxygen—roots would not be able to breathe if the surface were sealed. Permeability allows bacteria to set up home in the paving's pores—these life forms bioremediate many of the toxins imported from car oil and the like; tree roots and organic matter further enhance the bioremediation.[6]

Among the many ideas and case studies presented in this chapter, you'll see:

- How excessive impervious driveways and other paved areas can be made porous reduced in size, converted to gardens, or done away with entirely
- How neighborhood streets and rights-of-way are being transformed to function more like the watershed of a healthy forest than a street
- How communities are slowing traffic, controlling flooding, reducing the heat-is effect, and creating beauty in neighborhoods by planting trees in and along the streets where they are irrigated by runoff harvested from the streets
- And how parking lots can become parking orchards

At the very least, we can try to be observant of open-ground space between impermeable surfaces, where direct rainfall and runoff could be harvested (fig. 8.2), as well as try to actively reduce unnecessary impermeable surfaces (fig. 8.1), and use permeable pavement whenever possible so that rainwater falling upon these surfaces can be utilized by plants and infiltrate the ground.

Fig. 8.2. Verdant roadside forest where trees are otherwise scarce in dry southeastern Arizona. No one planted these trees. No one waters them. How is this possible? Available rainfall is tripled or more within the roadside swale thanks to captured runoff from the road. Runoff-, wildlife-, and wind-distributed seeds germinate where growing conditions are right.

Reduction of hardscape is explored first, then permeable paving, followed by more strategies to harvest hardscape runoff.

WHAT IS THE REDUCTION OF HARDSCAPE?

Hardscape reduction is a strategy to minimize the need for pavement through creative planning and design, and to remove impervious pavement, where possible. By reducing hardscape (and sloping it toward adjoining earthworks), you can increase the adjoining pervious areas to enhance on-site water infiltration of the hardscape's runoff, reduce runoff leaving the site that would otherwise contribute to downstream flooding and contamination, and decrease the heat-island effect caused by excessive, exposed hardscape. Considering how to decrease hardscape should be the first step in planning any paving projects.

WHERE IS HARDSCAPE REDUCTION USED?

It is used wherever there is excessive pavement. Here are some strategies to consider:

Reduce driveway paving to parallel wheel tracks

A "wheel-track" driveway can reduce impermeable surface area by 60% compared to conventional concrete driveways.[7] Just leave the center strip of the driveway unpaved, and if you like, cover it with vegetation or gravel (fig. 8.3). Go further still and limit the driveway's length to that of your parked vehicle so the shortened *drive*way simply becomes a *park*-way.

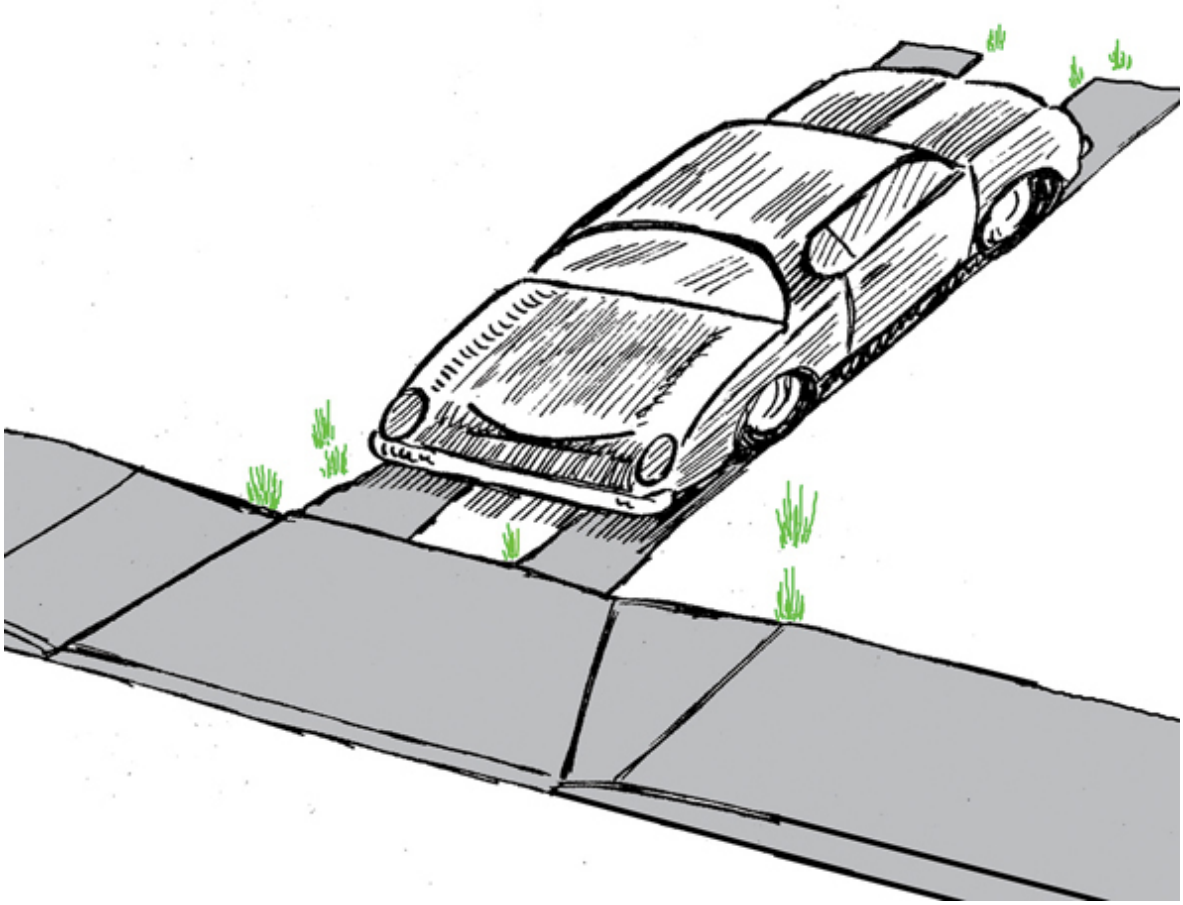


Fig. 8.3. A two-track (wheel-track) driveway paves 60% less area than a conventional fully paved driveway. Limiting it to length of vehicle further reduces pavement.

Eliminate the need for a driveway

Use the street as a city-maintained driveway and parking space by parking along the curb. Then eliminate your driveway and use this area for other purposes.

Eliminate the need for a car and associated paved surfaces

Use your feet, a bicycle, friends with cars, a community car-share program, and public transportation to reduce or eliminate your household's need to own motorized vehicles. This could save you $8,500 or more a year in costs for car

insurance, maintenance, fuel, and payments.[8,9,10] Lobby your local government to provide public transportation, integrated infrastructure, and land-use plans that maximize the convenience, safety, and comfort of bicycle and foot traffic linked to public transport.

Information sources for alternatives to car ownership and land uses that require paving can be found in appendix 4.

Plant along sidewalks and within medians

Public rights-of-way, street medians, and sidewalks can all be made more beautiful, pervious, comfortable, and healthy by planting indigenous shade trees (fig. 8.4). According to the National Wildlife Federation, "There are about 60 to 200 million spaces along our city streets where trees could be planted. This translates to the potential to absorb 33 million more tons of CO_2 every year, and saving $4 billion in energy costs [from reduced mechanical cooling and flood control infrastructure]."[11] Food-producing trees can enhance local food security at the same time. Vines can be planted where space is limited.

Fig. 8.4. Narrower streets and young native food-producing mesquite trees irrigated by harvested street runoff. Civano neighborhood, Tucson, Arizona. Arrow denotes water flow.

For a multipurpose alternative to curb and gutter drainages, see the Real-Life Example in this chapter from Seattle, Washington, and resources related to it in appendix 4. In Tucson, Neighborhood Foresters and Desert Harvesters are promoting street-grown food; see DunbarSpringNeighborhoodForesters.org and DesertHarvesters.org. Search "Streetside Water-Harvesting Image Gallery" at HarvestingRainwater.com for more examples.

Reduce width and shade streets

Plant trees in the streets; it's legal! Construct traffic-calming circles, chicanes, chokers, and buildouts within residential streets. Search "traffic calming" online for examples. Talk to your local traffic engineering department for information on the design and approval process, and potential funding. Enhance these traffic-calming strategies by incorporating water harvesting. If devices are placed at the high point of a crowned road from which water drains *away*, circle them with a raised curb, while the soil within is lower than the curb—to keep the water around (fig. 8.6). If the traffic-calming strategies are placed in low areas that water drains *toward*, set the curbs of these structures flush with the pavement or make cuts in the curbs to allow runoff to flow into the circles and buildouts (figs. 8.5, 8.7, 8.8). Depress the earth within planting areas and plant climate-appropriate shade trees. All this makes neighborhoods safer, cooler, and more beautiful. Search "Water-Harvesting Traffic Calming" at HarvestingRainwater.com for more examples.

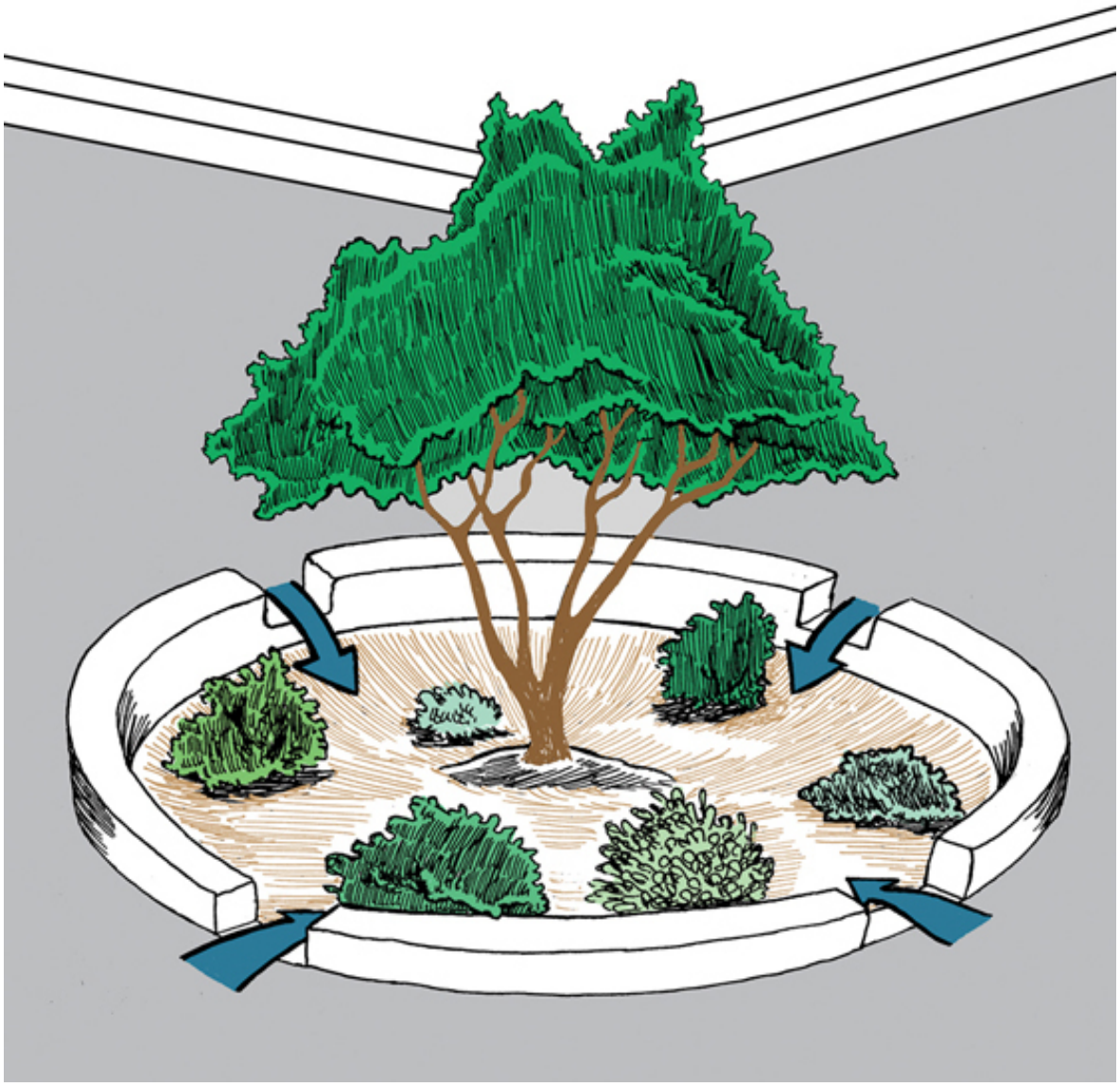


Fig. 8.5. Traffic circle in concave intersection (center of road is lower than sides of road). Raised curb keep cars out; curb cuts let water in. Alternative would be curb no higher than street and perimeter bollards or boulders spaced 4 feet (1.2 m) apart to keep cars out.

Fig. 8.6. Traffic circle in convex intersection (center of road is higher than sides of road). Raised curb (and sunken, mulched basin within) retain rainfall that would otherwise run off. Curb cuts let in runoff flowing along the high crown or ridge of the road.
Note: the construction of this circle reduced the paved area of the intersection by 26%!

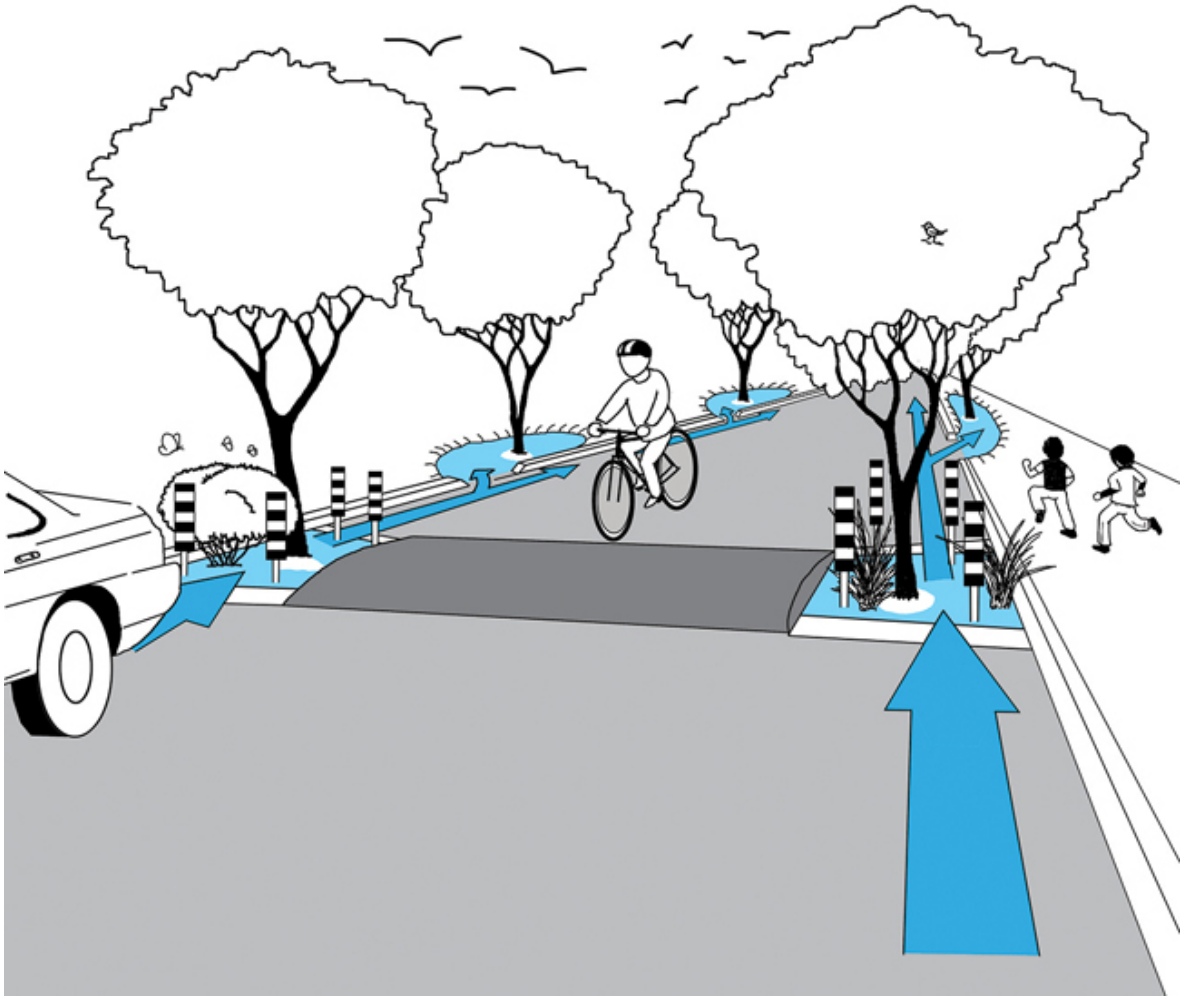


Fig. 8.7. Water-harvesting, traffic-calming chicanes bordering speed hump; along with shade trees within chicanes and street-side basins

Fig. 8.8. Chicanes or buildouts with flush curbs. Used where road is crowned or raised in the center and drains runoff to streetside curb. Flush curb allows runoff to infiltrate soil of planting area, while surplus runoff continues down the street. These chicanes calm traffic by forcing it to meander.

T-shaped "hammerhead" turn arounds take even less space, but require vehicles to make three-point turns.[12]

Promote smaller cul-de-sacs

Reducing the turning radius of a cul-de-sac (a turnaround or dead end) from 40 feet (12 m) to 30 feet (9 m) reduces impervious paving by about 50%.[13]

According to the Best Management Practices of the Metropolitan Council's Environmental Services website, a 40-foot (12-m) turning radius works for most emergency, maintenance, and service vehicles, while a 30-foot (9-m) radius requires the largest of these vehicles to make one backing movement to turn around.[14]

Promote landscaped islands within cul-de-sacs

Depressed water-harvesting landscapes can be created in the untraveled center of cul-de-sacs. A flat concrete curb flush with the level of the street stabilizes the

pavement and allows runoff to flow into the cul-de-sac's open center (fig. 8.9).

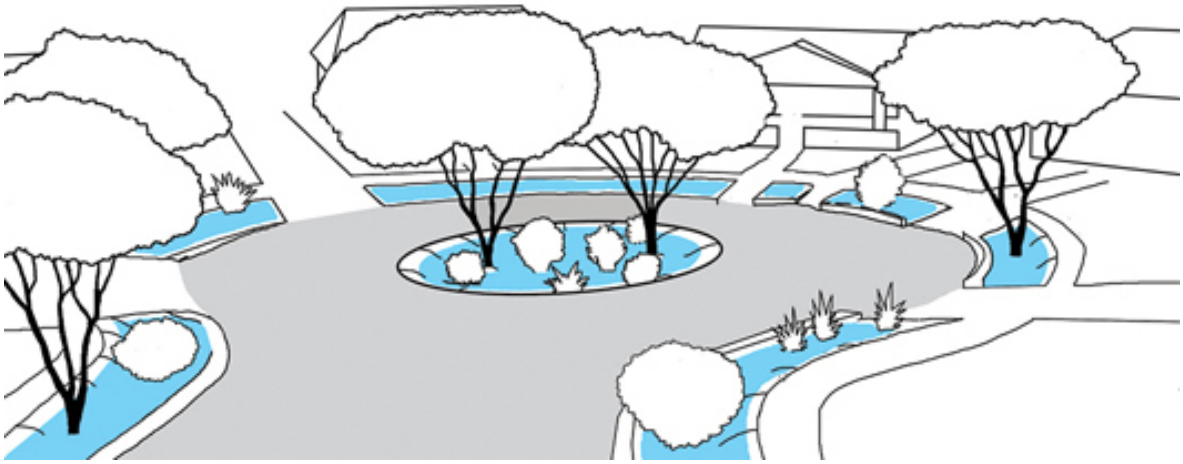


Fig. 8.9. Sunken planting island in a cul-de-sac

Encourage automobile alternatives

Advocate for the installation of convenient, shaded bike racks, bike paths, footpaths, and bus stop shelters to encourage less resource-consumptive modes of transportation and reduce the number of required parking spaces.

Fig. 8.10. Snow shows us unused paved areas that can be depaved, and brought to life. Credit: Jon Geeting from his blogged essay "What Snow Tells Us About Creating Better Public Spaces"

Reduce parking space dimensions

Position compact car spaces close to building entryways while placing parking areas for larger vehicles a little farther away. This rewards folks who are minimizing resource consumption. Determine the most space-efficient parking design for each site, which may include angled parking to reduce driving lane width.[15] Create triangular tree basins at the end of the angled parking spaces.

Promote shared parking lots

Parking lots can be shared by businesses and organizations whose peak parking demands occur at different times, such as offices needing weekday parking and restaurants needing primarily evening and weekend parking.[16]

Slope pavement to drain into landscapes

Any paved surface can be designed to drain toward sunken landscaped areas rather than straight to the street or storm drain (figs. 8.11, 8.12).

In the next chapter, fig. 9.25 provides a diagram of this concept.

Fig. 8.11. Pavement sloped to provide runoff water for pavement-shading trees. Ben-Gurion University, Israel. Less pavement would be another improvement.

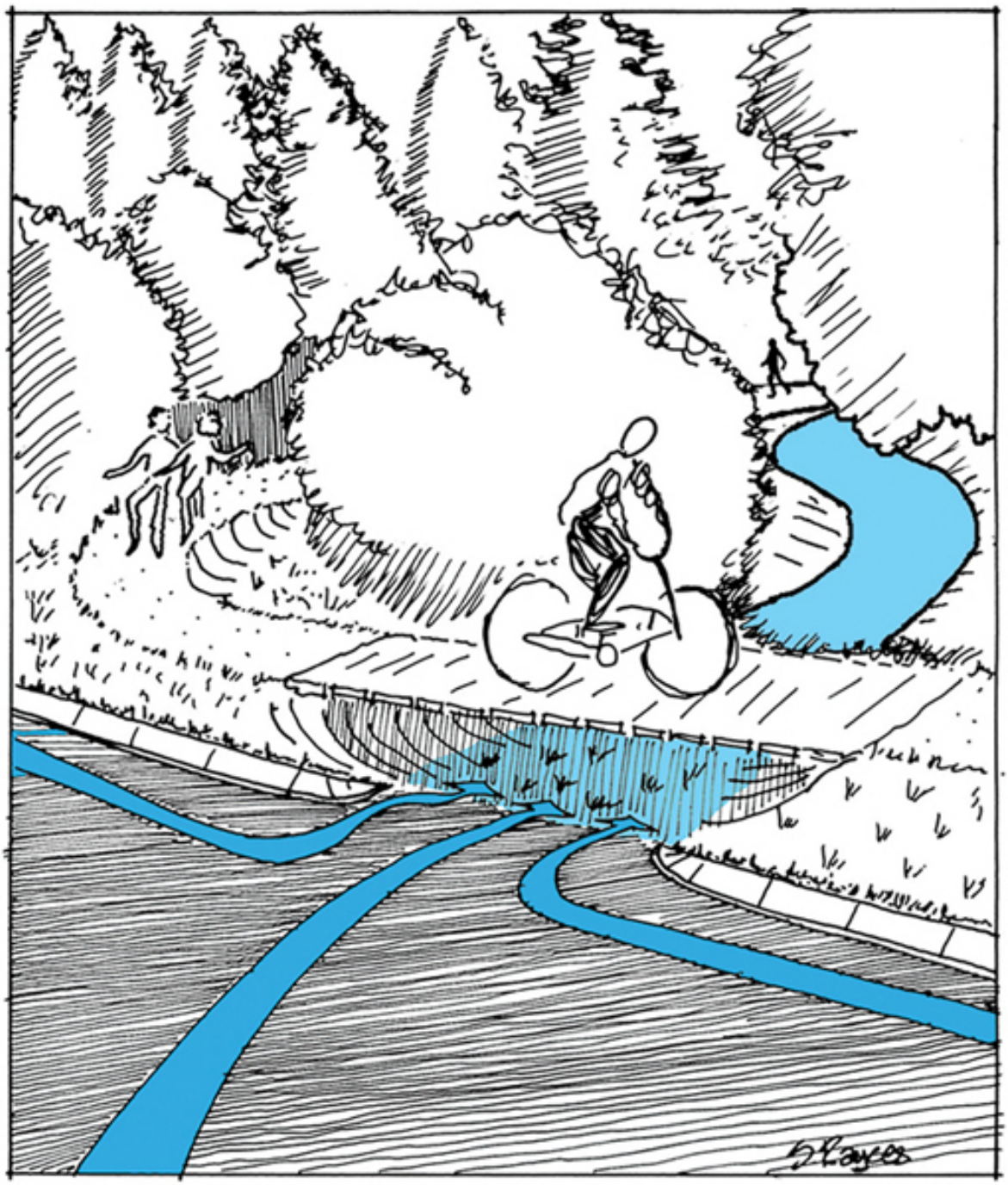


Fig. 8.12. Opening in curb directs street runoff to diversion swale irrigating the landscape. Village Homes, Davis, California. See Real Life Stories in chapter 9 for more.

Reduce building footprints

We can design and construct more efficient and elegant buildings by building smaller and smarter. This saves material costs, and less energy is needed for heating, cooling, and maintenance. *Cohousing* homes share exterior walls with one another, and residents share a community pool, common rooms, the use of a common clubhouse with an entertainment center, and laundry facility—this way these single shared facilities can take the place of many in each individual home. *Clustered developments* and garden cities limit development to one or several dense areas, leaving the rest of the site open for green space, wildlife habitat, and/or agricultural land supporting the community. See appendix 4 for cohousing, garden-city, and small-house resources.

The automobile dominates much of our lives, resulting in our homes, communities, and quality of life taking second place. This can be seen where closed garage doors rather than front porches greet visitors to our dwellings, where driving to the neighbor's or the local store is perceived to be safer or easier than walking or riding a bicycle, and where air and water quality are worsening (see box 8.1). See appendix 4 for more sources of information for alternatives to car ownership, excessive automobile use, and paving.

Box 8.1. Gasoline and Oil Facts

- Approximately 10 gallons (or 10 liters) of water are required to manufacture 1 gallon (or 1 liter) of gasoline.[17]
- One gallon (or 1 liter) of oil can contaminate up to a million gallons (or a million liters) of water.[18]
- 20 pounds (9 kg) of carbon dioxide (CO_2) emissions are generated from 1 gallon (3.8 liters) of gasoline.[19]
- An average tree stores 13 pounds (5.8 kg) of carbon every year and a community forest can absorb enough carbon dioxide to compensate for driving a car 26,000 miles (41,800 km). this time in history, the burning of coal, gasoline, and other fossil fuels has added more carbon dioxide to the atmosphere than trees and oceans can absorb, and this is the principal cause of global warming.[20] Conversely, reducing our production of carbon, while growing more trees, leads to less global warming.

HARDSCAPE REMOVAL, TOOLS, AND MATERIALS

Basic tools to remove impervious pavement: include a pick-axe, 10-pound sledgehammer, shovels, and wheelbarrow. Jackhammers and backhoes make big jobs easier.

Hardscape Removal: Asphalt-driveway removal can usually be done by hand, and it feels great when you uncover the soil (fig. 8.13)! Drive a pick-axe under the edge of the paving and pry it up to crack the surface. When you see the dirt below you'll literally feel the earth take a big breath—or at least I do. If you are just cutting a hole in the asphalt, a concrete saw can be rented or hired to do the job to make nice clean cuts.

Fig. 8.13. Early water-harvesting retrofit in 1990s. Shade trees planted in a basin cut on contour in a once-continuous asphalt parking lot. A bunyip water

level was used to find the contour, and spray paint marked it before cutting. Parking bay strips were repainted to align with the basin. The speed hump (at far end of basin) acts as a diversion berm directing additional runoff into the basin. After one year, the trees could survive entirely on runoff from the building and remaining asphalt. This photo was taken three years after the trees were planted. Old Community Food Bank site, Tucson, Arizona. Photo and design credit: Dan Dorsey

The weak (and potentially toxic) asphalt should be recycled (see box 8.2). For breaking up thicker asphalt or concrete, use a sledgehammer, jackhammer, or even a backhoe to peel it up and drop it—which will break it.

Box 8.2. Where Can You Recycle Asphalt and Concrete?

Great question! For asphalt and concrete recycling, contact your city and state transportation departments or search the web. Better yet, try to beneficially reuse that heavy, nontoxic concrete on site. See fig 8.20 and Real-Life Examples in chapter 4.

If you work carefully breaking up concrete you can use the larger chunks as permeable paving (fig. 8.20), or to build one-rock dams or terraces (figs. 4.1, 4.18 in the terrace chapter). And this leads to the next part of this chapter: Permeable Paving.

WHAT IS PERMEABLE PAVING?

Permeable paving is a term for water-harvesting techniques using porous or non-contiguous paving materials to enable water to pass through and beneath the pavement and infiltrate into the soil. Among its advantages, permeable paving allows passive irrigation of adjoining plantings and lessens soil compaction under and around such paving. Tree roots beneath permeable paving can breathe, and—along with the porous pavement—filter pollutants. The huge surface area of the well-aerated and occasionally moistened porous pavement structure helps support a diverse ecosystem of life similar to that of natural soils, and this life can help biodegrade oils into carbon dioxide and water.[21]

Permeable paving also decreases the need for additional and expensive drainage and flood-control infrastructure, because water infiltrates into it rather than runs off it. Thus, the porous paving is its own drainage and flood-control infrastructure.

WHERE IS PERMEABLE PAVING USED?

Permeable paving enhances water infiltration in locations where conventional, impervious paving would otherwise be used. It is most useful on densely developed sites where there's not enough unpaved surface to capture on-site runoff within earthworks alone (fig. 8.14). Permeable paving is most effective when it harvests *only the rainwater that falls directly upon it*, without additional runoff from upslope areas. Raise the paving above the surrounding landscape to prevent settling or pavement displacement due to poor-draining subsoil, and prevent sediment-laden stormwater runoff from washing over and into the permeable pavement, plugging its pores.

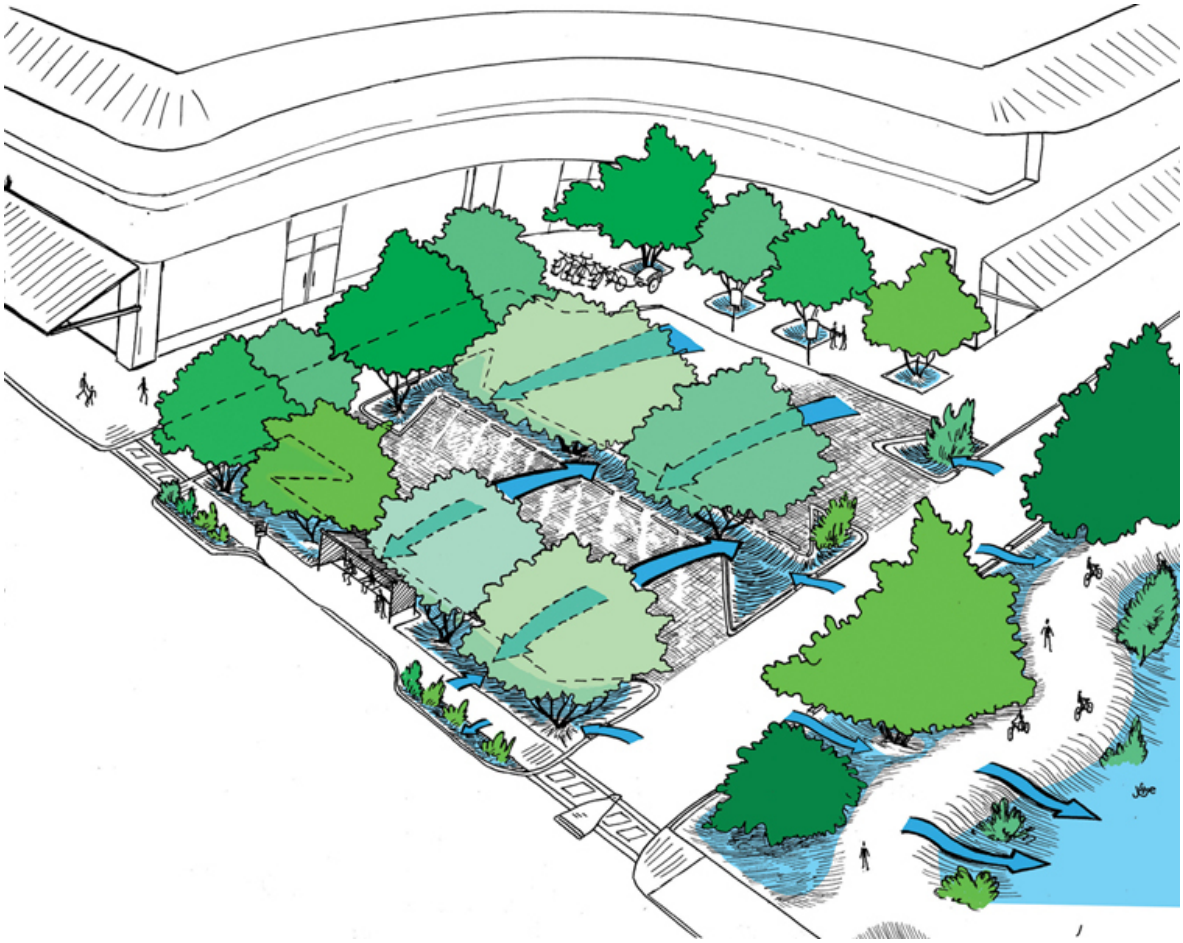


Fig. 8.14. Permeably paved parking lot, and impermeably paved raised road and path directing runoff to sunken vegetated basins. Planting of food-producing shade trees, such as velvet mesquite (*Prosopis velutina*) creates a rain-irrigated parking orchard. Note: Pattern of raised pavement and adjoining sunken planting area works with both permeable and impermeable pavements.

Porous pavement materials are best suited for areas of light traffic such as paths, driveways, parking stalls, and parking lanes, which can amount to approximately

half of the built cover in most urban land uses.[22] Permeable paving is ideal for use near or around shade trees, since it mimics a less compacted, healthy natural soil surface allowing the exchange of air and moisture throughout the tree's root zone.

WHERE *NOT* TO USE PERMEABLE PAVING

However, as Bruce K. Ferguson in his book *Porous Pavements*[23] recommends, the following types of settings should ordinarily be *avoided* when considering the use of permeable paving to infiltrate stormwater:

- Where slopes exceed 5% (3° or 19:1), and the subgrade could erode from water moving in the pavement
- On steep unstable hillsides where extra moisture could further destabilize the sl
- Over septic tank leaching fields where excess moisture could compromise the se system
- Over toxic soil deposits such as industrial *brownfields* that could leach contamir into the environment
- Where soil is so grossly permeable that it becomes a conduit for untreated wate into the groundwater
- Where a building's basement is within 20 feet (6 m) of the pavement, and coul flood from infiltrating water
- Where runoff is already being harvested from an impervious surface for direct u such as harvested runoff in adjoining earthworks that passively irrigate shade tr
- Where fill soil supporting heavy traffic could be weakened by excess moisture
- Where road crews spread pore-clogging sand or cinders for winter traction
- Where over-swelling soil could displace rigid concrete, paving blocks, or asphal (though this is typically not a problem for porous aggregate or soft porous pavi such as mulch)[24]

In addition, avoid:

- Drainageways
- Underlying soils that can't drain infiltrated water within 48 hours, or where wat tables are 3 or 4 feet (0.9–1.2 m) below the surface, hindering drainage[25]

WHEELCHAIR ACCESSIBILITY

All permeable paving materials discussed here can be made wheelchair-accessible if properly installed, though not necessarily American Disabilities Act (ADA)-compliant. There are ADA guidelines for permeable paving materials (for example there should not be more than a 1/2-inch (13 mm) gap between porous pavers).[26] Alternatively, pedestrian paths can be made of ADA-compliant materials, while using soft permeable paving, such as a screened mulch along the paths' borders for a peripheral/overflow material. For commercial products, see manufacturers' websites for updated information on ADA compliance.

PERMEABLE PAVING TOOLS AND MATERIALS

A number of material options are described in this section. Before buying permeable paving, research the applicability of different materials for your unique site and refer to manufacturers' instructions and information about material options and guidance on the tools needed for permeable pavement installation. Ask for references and verify the products' quality. Visit sites where the materials have been installed to see how they hold up, what worked, and what did not work. This is very important, because if you use a substandard product or use the paving in the wrong context you may need to replace it at great cost. Speak to those who install and use the material to get installation tips, learn about product performance, avoid costly mistakes, and get advice on obtaining permits (these may need to be experimental permits).

Tools: Refer to the instructions given in the options (below), and if applicable, manufacturers' installation instructions.

Materials: Some options for permeable paving materials and products:

Soft porous pavement or "mulch"

A mulched surface of woodchips, bark, and/or crushed shells (in coastal areas) is often the lightest-weight porous pavement. It provides a natural appearance and is easy to install and maintain. It biodegrades to help build soil, though it will need

to be reapplied more often than more durable materials. The light weight of these materials reduces delivery costs but potentially negates their use in exposed areas with high winds.

INSTALLATION TIP: Lay mulch no more than 1 to 2 inches (5 cm) thick (if thicker baby carriage wheels and the like can get bogged down in the material). If using crushed shells, lightly compact or tamp them to hold in place. If using woodchips, screened 1/2-inch (12-mm) minus-sized material is the easiest to walk and roll wheels upon. Larger-sized material, can be somewhat troublesome for those having walking disabilities. Contain the loose mulch material by placing it within a fixed border such as large rocks or tree branches anchored into the soil. A shovel, rake, and wheelbarrow are the basic tools needed.

APPROPRIATE USE: Mulch can be used along light traffic footpaths, within gardens (fig. 8.15), and on playgrounds if it meets ASTM F 2075 criteria to lessen the impact of a child falling onto the surface. Use mulch only in areas with less than a 3% slope. Mulched surfaces are not ADA-accessible.

Fig. 8.15. Raised garden path mulched with small wood-chips. Adjoining basins capture path runoff.

Porous aggregate

Porous aggregate (gravel) has the "highest permeability and the lowest cost of almost any permeable paving material,"[27] and is more durable than soft porous pavement (fig. 8.16). To be porous, permeable, and stable under a load, the aggregate particles must be angular in shape so their flat faces interlock with each other and resist rotating and shifting. "Crushed stone" or "crushed gravel" are appropriately angular materials, as opposed to smooth round "river stone" or "pea gravel," which rotate and slip past each other and "give" under a load (fig. 8.17A).[28] The aggregate must also be *open-graded* or *single-sized*, which results in the aggregate having a narrow range of particle sizes and open void spaces that improve interlocking between particles (fig. 8.17B).

Fig. 8.16. Porous aggregate under bike racks and trees in heavy pedestrian zone, University of Arizona, Tucson. Runoff from concrete sidewalk is harvested in porous aggregate, while sidewalk and curb help keep aggregate in place. Trees would benefit even more if the section of impervious concrete between pillars and palm tree was replaced with an extension of pervious pavement.

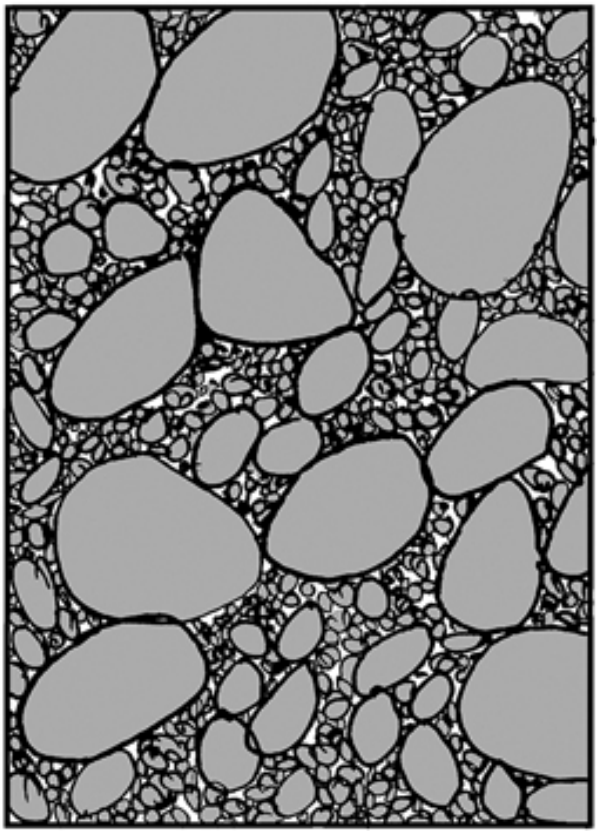


Fig. 8.17A. Round, mixed-size or dense-graded aggregate has little void space/water-capacity and is less stable

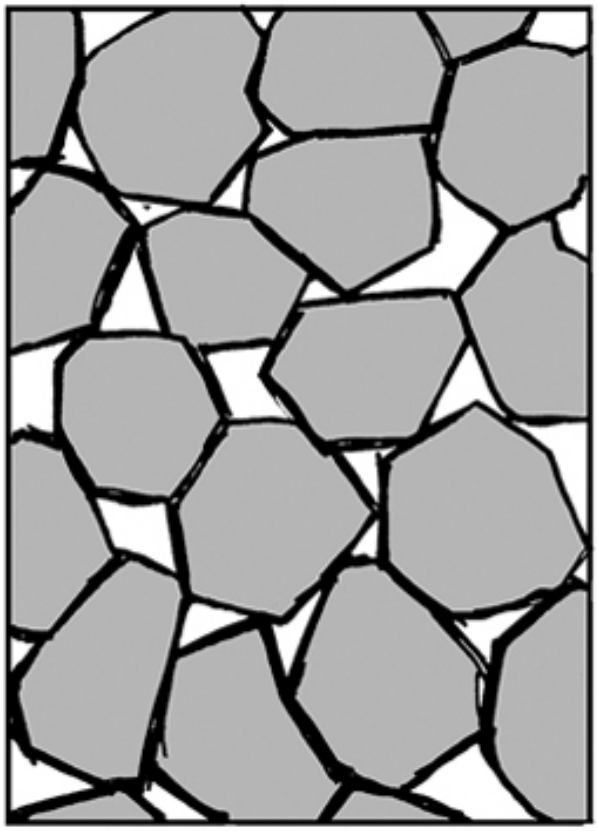


Fig. 8.17B. Interlocking, angular, single-size or open-graded aggregate has more void space/water capacity and is more stable

Make sure the open-graded gravel you select is durable enough not to wear down to finer material. Before delivery have it washed clean of fine particles that could clog the pores between the aggregate.

While aggregate with particle sizes up to 1 inch (2.5 cm) drains rapidly, 1/4-inch (6-mm) minus particles are much easier to walk on. One-quarter-inch (6-mm) and 3/8-inch (9-mm) minus decomposed granite stabilized with Stabilizer Solutions' natural Stabilizer binder has been approved by the City of Tucson and other municipalities for wheelchair-accessible public pathways.[29]

INSTALLATION TIPS: Porous aggregate is very easy to install and maintain with a shovel, wheelbarrow, rake, and hand-pulled lawn roller for residential pathways. A mechanical double drum roller is recommended to compact the material on commercial projects. Porous aggregate can be placed on compacted soil and the aggregate itself should also be compacted with the roller to reduce settling or shifting. In some cases it may be necessary to apply a state-approved base course of engineered fill before the porous aggregate is put in place to prevent

underlying soil from mixing with the aggregate and filling in pore spaces. Stabilized aggregate should be applied in a layer at least 6 inches (15 cm) thick if it will be regularly driven upon.

APPROPRIATE USE: Because porous aggregate can be displaced, do not use it on slopes steeper than 3%, and confine its use to very-low traffic areas such as pathways, residential driveways, lightly used parking stalls, long-term RV parking, and the grounds of plant nurseries. Contain the aggregate with a firm border such as concrete curbing, large rock, or strips of metal *structural edging*. Because of its flexible nature, aggregate works well over swelling soil, uncompacted soil, and tree roots, and in areas where soil heaving results from deep-freezing weather.[30] Non-stabilized porous aggregate is not ADA-accessible.

Plastic geocells

Plastic geocells are manufactured products designed specifically as a permeable paving material. The geocells are a connected matrix of open, plastic cells that can be filled with aggregate, soil, or turf. Some brands also include a backing of geotextile fabric. The geocell matrices come in panels or rolls that are laid on firm native soil or on a compacted porous base material of engineered soil, depending on the model and application (fig. 8.17A, B).

INSTALLATION TIPS FOR THE GRAVELPAVE[2] BRAND OF GEOCELL: Create a firm base course of porous engineered fill, similar in depth to what would be placed under asphalt. Roll the plastic matrix flat into place over the base course (fig. 8.18A) and secure it with long landscaping nails hammered into the soil at a rate of 4 nails per square meter. Using rakes and brooms, spread washed, open-graded, angular gravel over the matrix until it thoroughly fills the plastic rings and covers them with 1/4 inch of gravel (fig. 8.18B). Compact the aggregate into place with a hand-pulled lawn roller. The matrix reinforces the gravel material, reducing rutting, mud accumulation, and root-zone compaction. Acting somewhat like a snowshoe, it also spreads weight more evenly so heavy machinery such as fire trucks and garbage trucks can travel over the surface (when saturated with moisture) without it sinking. The erosion-control fabric reduces weed growth and keeps gravel from subsiding past the matrix into the potentially large open-graded aggregate sub-base. Volunteers led by a knowledgeable supervisor can typically do the installation once the underlying soil or base course is graded and in place. The

matrix is easy to install around obstructions by cutting it with ordinary hand or power tools, and it doesn't require special fasteners or connectors.

Fig. 8.18A. Gravelpave[2] geocells with landscape fabric backing being installed at Milagro Cohousing parking lot, Tucson, Arizona. Flush concrete curb will strengthen the edge between the geocell surface and the incoming stabilized-earth road.

Fig. 8.18B. Completed Gravelpave2 parking lot with geocells filled with gravel. There is no runoff from this parking lot, so no detention basin or other drainage was required. But since there is ample unpaved land around and within the parking lot, conventional impervious pavement could've been just as effective as porous pavement if it were sloped to evenly drain to high-capacity vegetated water-harvesting basins surrounding, and within the medians of, the parking lot. See the first Real-Life Example in chapter 2 for more on Milagro's water harvesting.

APPROPRIATE USE: Use Gravelpave[2] or another brand of plastic geocells for trails, horse paths, high-use pedestrian areas, residential driveways, light-traffic parking lots, commercial parking lots, and storage yards. The heavy duty Geoblock brand has been used successfully for ATV trails in Alaska and on mountain bike paths with slopes steeper than 25% (14˚) in Wisconsin.[31] The use of geocells allows the use of aggregate and turf in more demanding traffic settings than these materials could bear alone, such as emergency vehicle accessways.[32] See the resources appendix 4 for Gravelpave[2] and Geoblock contact information. Grasspave[2] is available for grass accessways.

Open-jointed paving blocks

These paving blocks are solid units installed with at least a 1/4-inch (6-mm) space or joint between them. The joint is filled with a quick-draining, open-graded angular aggregate or vegetated soil, or are left open for infiltration of water into a porous base course beneath the blocks. The blocks can be manufactured specifically for use as porous paving (fig. 8.19), such as open-jointed, interlocking concrete pavers, or you can use bricks, stone, or salvaged chunks of concrete installed with open joints (fig. 8.20).

Fig. 8.19. UNI Eco-Stone open-jointed paving blocks. Courtesy of UNI-GROUP U.S.A.

INSTALLATION TIPS FOR OPEN-JOINTED, INTERLOCKING CONCRETE PAVERS: It's best to have the installation done by a contractor experienced with interlocking concrete paving systems.[33] The contractor will first spread geotextile fabric over the subgrade. Next, the contractor will spread and compact a base course of open-graded (commonly No. 57 gradation[34]) angular aggregate over the fabric. The aggregate acts as the filtering and storage medium for runoff, minimizing damage from soils that heave when frozen. The geotextile fabric keeps the aggregate from mixing with, and having pore spaces clogged by, the soil below. Next, the contractor will lay down a maximum 1-inch (2.5-cm) thick layer of smaller open-graded aggregate as a level bed for the interlocking concrete pavers.[35] The pavers are then laid, the joints are filled with an angular porous aggregate (typically with a No. 8 gradation from ASTM D 448),[36] and a vibratory plate compactor is used to seat and level everything in place. Note*: Firm edging must be provided around the paved area* to hold the paving block and aggregate base course in place. See fig. 8.21.

Fig. 8.20. Salvaged chunks of concrete sidewalks are decoratively laid as a porous patio in the award-winning landscape of the Amado residence, Tucson, Arizona. Designed by Blue Agave Landscape Design

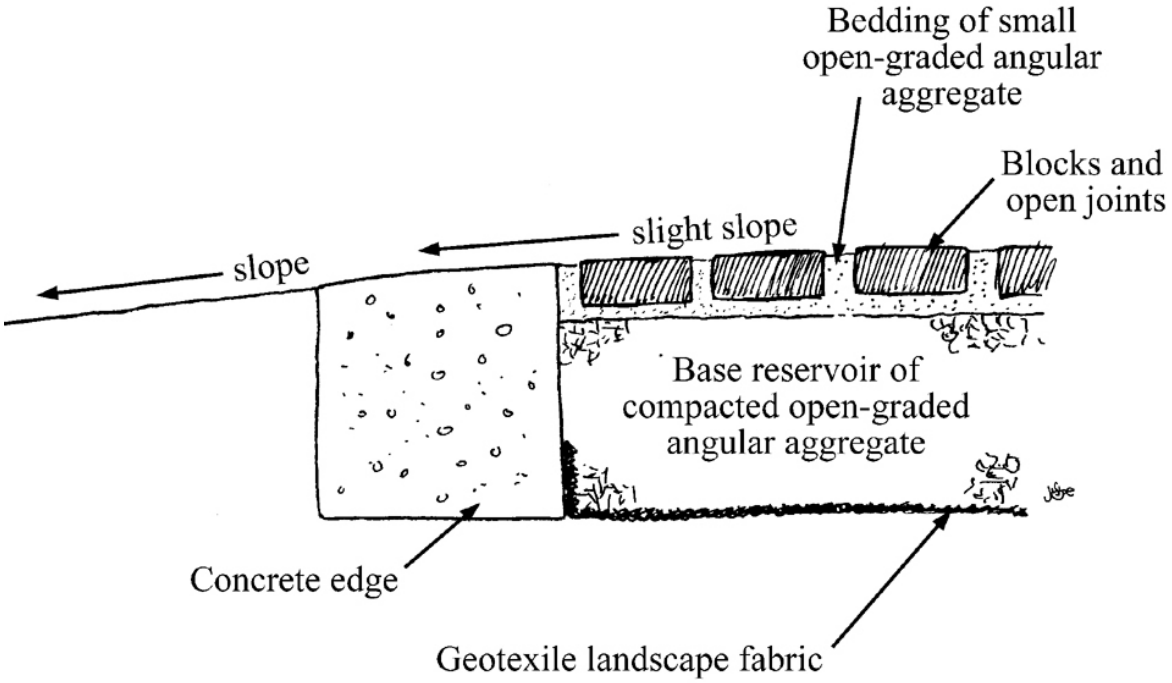


Fig. 8.21. Typical open-jointed paving block construction components. Adapted from *Porous Pavements*[37]

INSTALLATION TIPS FOR STANDARD BRICK, STONE, OR SALVAGED CONCRETE PAVERS: Grade the area to be paved to the desired slope and elevation, allowing for the thickness of the paving material, plus a 3- to 6-inch (7.5- to 15-cm) thick base course of washed, open-graded 3/8- to 1/2-inch (9- to 12-mm) diameter angular gravel. Lay the pavers with an open joint between them, then fill the joint with open-graded, washed angular gravel. If using salvaged concrete, choose flat "paving stone" pieces with a roughly uniform thickness of 4 inches (10 cm) or more to provide strength, a neat appearance, and easy installation. For step-by-step instructions and photographs on laying the concrete, bricks, or stone see David Reed's comprehensive book *The Art and Craft of Stonescaping: Setting and Stacking Stone*.

APPROPRIATE USE: Use open-jointed, interlocking concrete pavers for paths, patios, entryways, plazas, driveways, parking lots, cul-de-sacs, light-traffic residential streets, and loading docks. They are a durable material with a long

service life, and the stable, interlocking concrete pavers can handle heavy loads such as water-laden fire trucks in a variety of climates. Use standard brick, stone, or salvaged concrete pavers laid with an open joint for light-traffic paths, patios, and residential driveways. All open-jointed paving blocks provide access to underground utilities, and the paving material can be put back in place when utility work is complete.

See the resources appendix 4 for suppliers of open-jointed, interlocking concrete pavers. For a more thorough description of the permeable paving options listed above; additional options including porous concrete, porous asphalt, and others; products; performance; cost; installation; maintenance; and case studies, I highly recommend the comprehensive book *Porous Pavements* by Bruce K. Ferguson, CRC Press, 2005.

STEPS TO INSTALL PERMEABLE PAVING

As reported in the *Stormwater Journal*, porous paving expert Bruce Ferguson stresses three things must be done with each porous pavement installation:

1) Select for location

2) Make sure the design is correct

3) Build properly

"If you do all these things right, there is no reason to expect failure," Ferguson adds, "If you do any one of them wrong, it probably will fail.[38]

SITING

Plan for, and grade, the surface of the paved area and the subsurface beneath to drain surplus water away from adjacent buildings and downward and away from the paved area toward vegetated water-harvesting earthworks placed at least 10 feet (3 m) from buildings. Standard pavement slopes range from a 1/8-inch (3-mm) to a 1/4-inch (6-mm) drop per horizontal foot (30 cm). Permeable paving is most effective when it harvests only the rainwater falling directly on it, without receiving additional runoff from upslope areas, though a limited amount of sediment-free runoff from impervious roofs and pavements is acceptable.[39] Sections of permeable paving may settle or become displaced if too much water infiltrates and the subsoil doesn't drain sufficiently. In addition, silts flowing onto

the paving clog the small spaces between the porous pavement, so all permeable paving surfaces should be raised above the immediately surrounding landscape. Permeable paving may be paired with water-harvesting earthworks such as berm 'n basins or infiltration basins that are placed upslope to catch sediment-laden runoff before it reaches the paving, and infiltration basins or boomerang berms placed downslope of the paving to receive excess water running off the paving. (Compare figs. 8.22A and 8.22B.)

Fig. 8.22A. *Bad.* Runoff and sediment misdirected over pavement. If this is porous pavement, its pores will clog with the sediment.

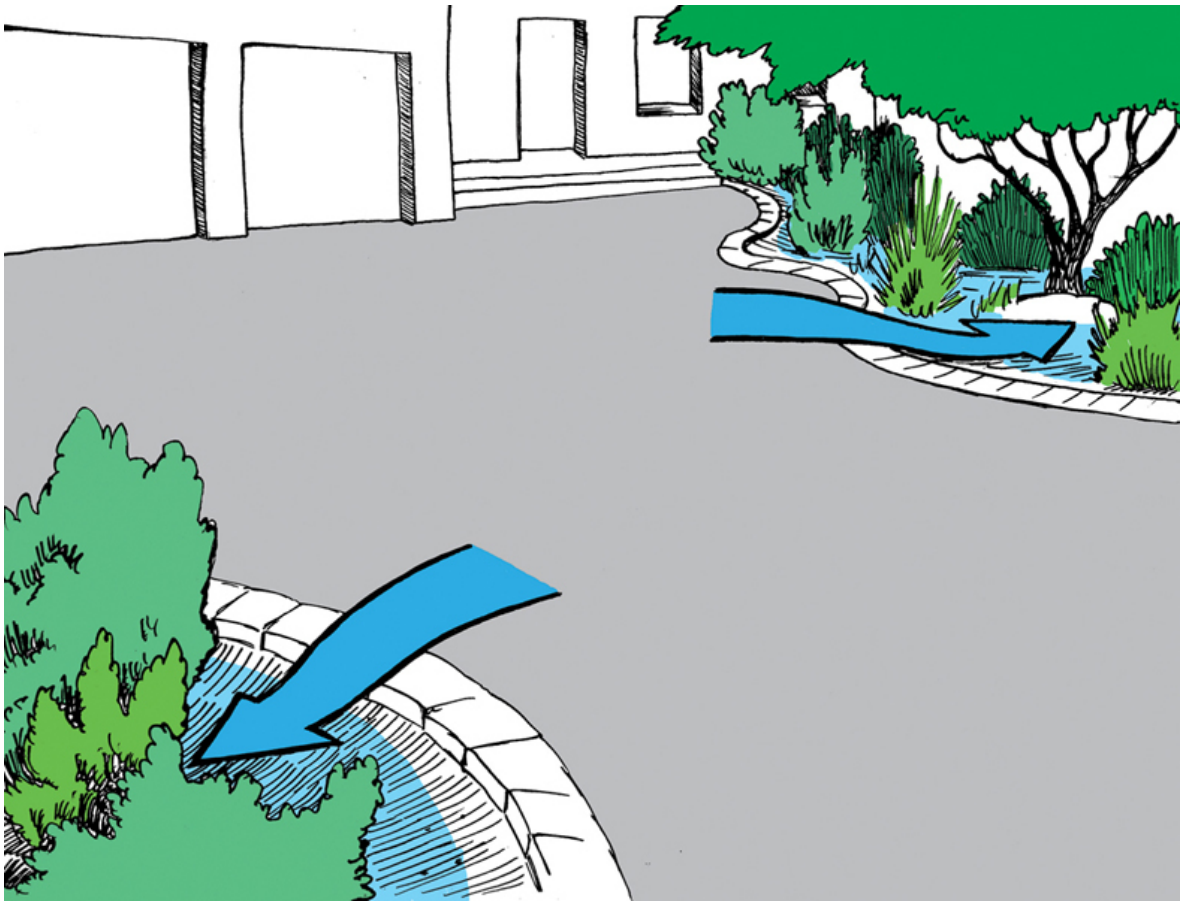


Fig. 8.22B. ***Good.*** **Runoff beneficially directed to sunken vegetated basins**

SPACING

If locating the paving beside a wall or building, place its top surface at least 6 inches (15 cm) below the top of the adjacent stem wall or floor level to reduce rainwater splash and potential wall damage.

CONSTRUCTION

Installation of permeable pavement will vary depending on materials used. Refer to the manufacturer's specifications and the requirements of your local building authority.

Multilayered pavements should have each successive lower layer extend beyond the edge of the layer above (fig. 8.23).[40]

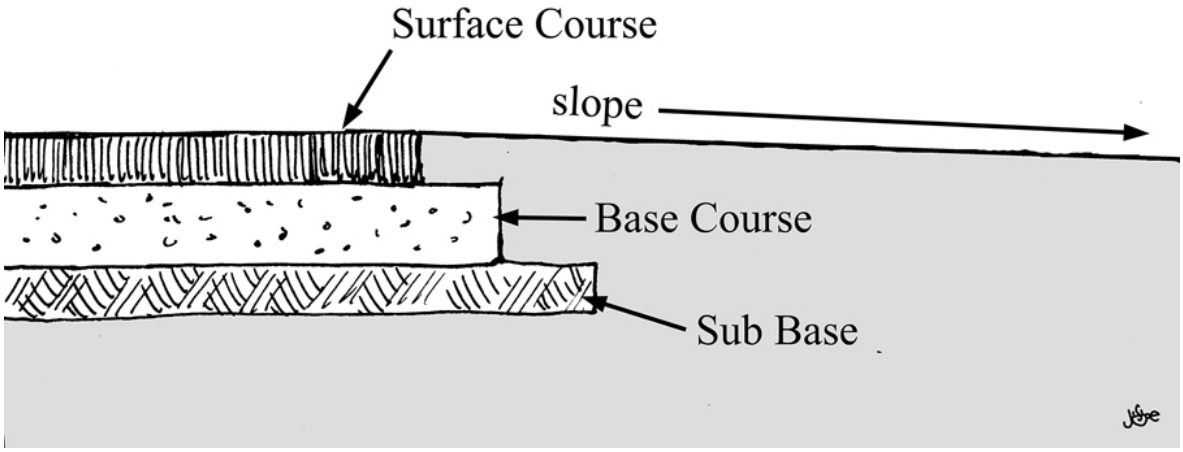


Fig. 8.23. Lower layers extend beyond upper layers.
Adapted from *Porous Pavements*[41]

LOCATION AND CONSTRUCTION OF OVERFLOW SPILLWAYS

Overflow from porous paving should be directed to adjacent water-harvesting earthworks such as infiltration berms, berm 'n basins, or diversion swales. The edges of the paving are often stabilized with concrete curbs, brick, or stone mortared in place so that overflow will not undermine the paving (fig. 8.24).

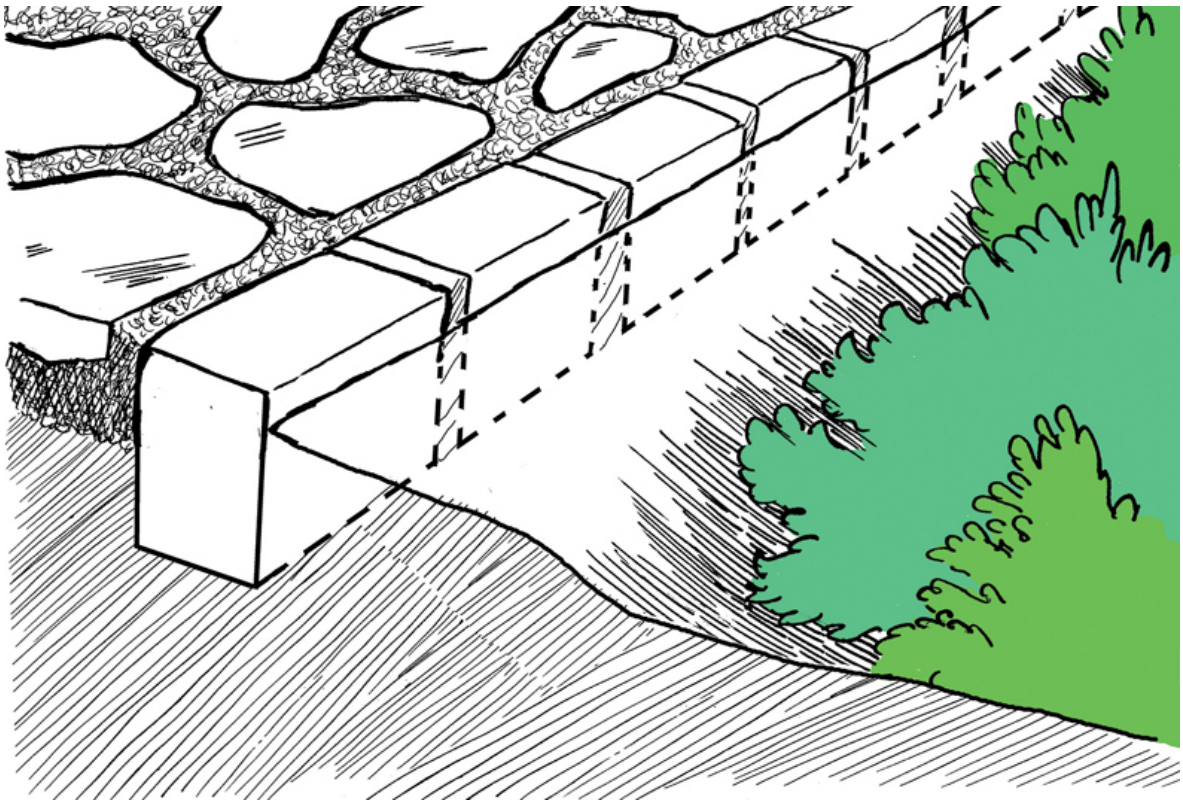


Fig. 8.24. Stabilized edging (curb) for a porous pavement of salvaged concrete set in gravel

PLANTING PERMEABLE PAVING

In wet climates, grass is often planted in the joints between some permeable paving, such as Grasspave[2] (these porous pavements with grass are intended for alleys and parking spaces, not sidewalks, and the grass is supposed to cover the pavement or matrix that supports heavy loads of big trucks). I don't recommend this in drylands because the harsh microclimate of the pavement would necessitate regular watering. Instead, I recommend porous pavements that are not planted, such as porous aggregate or Gravelpave[2]. The planting is then located adjacent to —not in—the paving. For instance, low-water-use native vegetation could be planted in adjacent water-harvesting infiltration basins. Vegetation anchors soil, uses the harvested water (that has percolated below the paving surface), shades the paving, cleans the air, reduces glare and noise pollution, provides wildlife habitat, and adds beauty and comfort.

Trees and permeable paving are very compatible. For a tree to grow to its natural mature size and live a full life, its root zone (at a 24-inch or 61-cm depth) should be at least as large as the area expected under the tree's canopy at full maturity.[42] This is not possible when the tree's roots are unduly surrounded and confined by impervious paving and its compacted subsoil, since the sealed and compressed soil can no longer provide the needed storage and the transfer of air, water, and nutrients. However, less compacted, non-sealed soil covered with porous pavement can still act like natural soil, allowing roots to extend as far as they need. There are also special subsoil mixes that can be utilized beneath porous paving to further enhance root growth (see structural soils in Variations section of chapter 5).

MAINTENANCE

Keep paved areas relatively free of debris that could clog the pore spaces between paving materials. Sweep leaves and other plant litter into adjacent basins where it can serve as mulch. If excess runoff and sediment washes over the pavement, construct other water-harvesting earthworks upslope to capture and infiltrate that runoff before it gets to the pavement.

MULTIPLE FUNCTIONS OF REDUCED HARDSCAPE AND PERMEABLE PAVING

REDUCING THE HEAT-ISLAND EFFECT

The heat-island effect occurs in heavily paved and developed areas when the full power of the sun heats up, and becomes stored in, the thermal mass of exposed sidewalks, pavement, and buildings with little or no sheltering vegetation. That stored heat is released in late afternoon and evening, keeping summer evening temperatures as much as 10°F (5°C) higher than normal.[43,44]

In urban and suburban areas the best strategy to reduce the heat-island effect is to reduce hardscape and plant shade trees and other vegetation that will canopy over and shade the hardscape. Note that trees use less water and provide more cooling than turf.[45] Enabling the planting of more sheltering trees throughout a paved area, and enhancing their growth potential through the use of permeable paving, works where paving must be maintained.

CONTROLLING FLOODS AND POLLUTION

Impervious cover increases the speed at which watersheds drain, leading to downslope flooding. For example, in 1886, when agricultural and urban development covered only 10% of a portion of the Des Plaines River watershed in Illinois, the river's median annual discharge was 4 cubic feet (0.11 cubic meters) per second. Today, with development covering 70 to 80% of that area, the median annual discharge is 700 to 800 cubic feet (19.8 to 22.6 cubic meters) per second —175 to 200 times the earlier discharge level.[46] And, much of that runoff is contaminated. The U.S. Environmental Protection Agency ranks urban runoff and storm-sewer discharges as the second most widespread source of water quality impairment in our nation's estuaries, and the fourth most common source in our lakes.[47]

It doesn't need to be this way. Studies in Ontario, Canada, found that permeable pavement can reduce runoff volume by 90% and yield significantly cleaner runoff water when compared to impermeable paving surfaces.[48] But pollutants don't just vanish, so our ultimate strategy should be to keep contaminants out of our air, soil, and water in the first place. Minimize car use, and fix leaks that could drip chemicals through permeable paving into soil or water. Minimize or avoid using herbicides, pesticides, and other chemicals, and dispose of them properly.

Web links to photos and publications of integrated sustainable stormwater projects are in appendix 4.

REDUCING COST

According to porous pavement expert Bruce K. Ferguson, "A porous pavement with little or no drainage structures is commonly less expensive than a dense pavement with the large drainage and treatment systems it requires."[49]

IMPROVING SAFETY

Vehicles and pedestrians have better traction on a porous pavement in wet weather than impervious pavement with a sheet of water on it. Thus all interstate highways in Georgia and Oregon are repaved with an overlay of porous asphalt, which increases the carrying capacity of the roads in wet weather by reducing the risk of vehicle hydroplaning.[50]

REAL-LIFE EXAMPLES OF REDUCING HARDSCAPE, HARVESTING ITS RUNOFF, AND CREATING PERMEABLE PAVING

DRIVEWAY GARDENS—LOS ALAMOS, NEW MEXICO

A radical change has occurred at the suburban home of Mary and Charles Zemach in Los Alamos, New Mexico (where average annual precipitation is 18.9 inches or 480 mm at 7,200 feet or 2,194 m elevation). Workers removed half of a four-car-wide concrete driveway, a lawn, a cement walkway, front steps, and brick planters that used to dominate the front yard. The broken-up concrete was then reused to create water-harvesting terrace walls throughout the sloping back yard (see examples in chapter 5). But more was needed, so another 35 tons of broken concrete were salvaged from the landfill to complete terraces and line garden paths. Admiring the uniform thickness of the salvaged concrete, Mary remarked, "Just stack them up like bricks. They're much easier to use than odd-shaped rocks." The terrace walls support a permeable patio of flagstone and numerous well-vegetated infiltration basins.

The result is a verdant outdoor gathering area and landscape designed by Ben Haggard and implemented by permaculture landscaping firms (fig. 8.25). Well-mulched infiltration basins and contour berms have replaced a driveway section and lawn. Runoff from the remaining section of driveway is directed into two infiltration trenches and a diversion swale. Dryland-adapted perennial plantings burst with color, fruit, and fragrance. A permeable flagstone ramp meanders through the plantings, making the garden wheelchair accessible. Abundant veggies and 30 fruit trees sprout from terraces and from the edges of infiltration trenches

and rock wicks filled with rubble from the demolished brick planters and driveway. The old lawn became mulch.

Fig. 8.25A. The Zemachs in the garden where their driveway used to be

Fig. 8.25B. The Zemach yard planted with food-producing shrubs and fruit trees (on the left) is watered less often and with less supplemental water than neighbor's lawn on the right.

Mary's garden provides fresh organically grown food for her family all year long, and she freely gives away the surplus. Thanks to the water-harvesting earthworks, she has never watered her productive yard more than ten times a year, applying an inch of water per watering. Yet her neighbor's lawn is often watered daily in summer. Summing up her strategy, Mary says, "The cheapest way to store water is to get it into the soil as fast as possible." (See fig. 8.25.)

Chapter 5 in *Gaia's Garden: A Guide to Home-Scale Permaculture* by Toby Hemenway is about the Zemachs, and the cover photo features Mary's yard.

A MULTIPURPOSE ALTERNATIVE TO CURB AND GUTTER DRAINAGES— SEATTLE, WASHINGTON

The Street Edge Alternatives (SEA) and Green Grid projects in Seattle, Washington, (average annual rainfall of 36 inches or 914 mm) have created 20 blocks of an alternative neighborhood-street design that uses pavement reduction, water-harvesting earthworks, and native salmon-friendly plantings in combination

with traditional drainage infrastructure. The result is an area that functions more like the watershed of a healthy forest than a suburban street.

Within the project sites, existing linear streets, with open drainage ditches and culverts on either side, were realigned to a curvilinear path narrowed to 14 feet (4.3 m) (18 feet or 5.5 m at intersections), wide enough for two standard cars to pass each other slowly. A concrete sidewalk mirrors the curvilinear street on one side only, to further minimize impervious paving. All remaining areas within the right-of-way are used to detain and infiltrate stormwater. The old drainage ditches have become meandering diversion swales and rain gardens that lengthen the flow path of runoff, while mulch and native plantings welcome the water into the soil. This reduces downstream flooding, filters contaminants, enhances wildlife habitat, and provides the landscape with most of its irrigation needs.

The impervious surfaces along the street have been reduced 11%, and over 100 trees and 1,100 shrubs have been planted. Rain infiltrates on site and is utilized by the vegetation, eliminating over 98% of the once-problematic stormwater runoff. People enjoy the beautiful landscapes so much there is now big public demand for such work to extend into other streets and neighborhoods. Salmon benefit from the reduction of pollutants and sediments flowing into streams. The rewards of this project are diverse and the cost was comparable to traditional curb, gutter, and sidewalk street improvements.[51] (Compare figs. 8.26A, 8.26B, and 8.26C.)

Fig. 8.26A. Seattle, Washington, street before the Seattle Street Edge Project. Courtesy of Seattle Public Utilities

Fig. 8.26B. Seattle street right after Seattle Street Edge Project. Courtesy of Seattle Public Utilities

Fig. 8.26C. Same street in summer 2005

For more on the Seattle SEA project and similar projects elsewhere, see appendix 4.

GREEN STREETS AND GREEN PARKING LOTS—PORTLAND, OREGON

The Green Streets projects in Portland, Oregon, (average annual rainfall of 36 inches or 914 mm) is using Natural Drainage Systems design (figs 8.27 - 8.29) to recognize and capitalize on what urban roadways often are—ephemeral waterways. Thus, they are designing curb cuts into both new and retrofitted street-side curbs. These direct street runoff into mulched street-side infiltration basins in which native shade trees and other plantings are planted to filter, infiltrate, and utilize the water to then grow a canopy of summer shade over the street and sidewalk. And it doesn't stop there. They are also calming traffic and increasing plantable green space by narrowing residential streets with buildouts and median plantings, creating water-harvesting parking lots and parking garages growing a living carport of adjacent shade trees, and more. See appendix 4 for additional information, including web links to their downloadable self-guided bicycle and car tours of sustainable stormwater strategies throughout the city.

Fig. 8.27. Curb cuts along a residential street beside the People's Co-op, Portland, Oregon. Sidewalk strip beside curb allows for easy access of people entering and exiting cars parked along curb, while steel scupper directs runoff water to vegetated infiltration basin. Raised curb alerts pedestrians to edge of basin.

Fig. 8.28. Curb cuts along an arterial street beside the New Seasons Market direct runoff into adjoining mulched and vegetated basins. Portland, Oregon

Fig. 8.29. Water-harvesting parking lot, New Seasons Market, Portland, Oregon. Parking area drains to adjoining sunken, mulched planting areas. Wheel stops keep cars out, but let water pass by. Trees are planted on slope so their roots can access the harvested water, while their root crowns are well drained. As trees grow, they will canopy over the asphalt.

WATERING STREET TREES WITH STREET RUNOFF—TUCSON, ARIZONA

Rainwater harvesting can lead to dramatic change. When my brother Rodd and I purchased our Tucson home in 1994, it was bordered on two sides by a 20-foot-(6-m) wide bare dirt public right-of-way acting as a haphazard neighborhood parking lot. Then we began harvesting water in the soil. Now we are bordered by beautiful native shade trees that arch over a meandering footpath and the adjacent street. Native birds nest and sing in the branches. Neighbors smile and wave as they stroll by.

Before we started, the land between our property and the street was heavily compacted and all runoff drained into the street, which in turn drained storm-

water out of the neighborhood (boxes 8.3 - 8.8). In big storms the section of the street along the curb became a strong flowing stream, and properties downstream risked being flooded.

Box 8.3. Tapping Into the Rivers of Runoff Along Our Streets

In an average year of rainfall (12 inches or 305 mm), the runoff from rain falling on my neighborhood's streets equals over 1.25 million gallons per mile (or 3.46 million liters per kilometer)!

In my climate, that's enough runoff to provide all the irrigation needs of 422 established 20-foot (6-m)-tall trees per mile (1.6 km), or a tree every 25 feet (7.5 m) lining both sides of the street.

So we've started to tap that runoff to passively and sustainably irrigate street-side shade trees, which will turn hot and sterile strips of asphalt into cool and beautiful greenways that solve flooding and water quality problems instead of creating them. You can do the same.

See the estimates below or box 1.4 in chapter 1 to calculate the runoff volumes in your streets. The estimates above are based on 12 inches (305 mm) of rainfall, an average residential street width of 38 feet (11.4 m), a 0.85 runoff coefficient for the impervious asphalt street surface, trees with 20 foot (6 m) heights and canopy diameters— each needing 3,000 gallons (11,370 liters) of water per year, and spacing the trees 25 feet (7.5 m) apart. The water needs of the trees were calculated with the information and tables in appendix 4 of Volume 1. Trees' water needs will vary with tree type, tree size, and climate.

Note: The calculations do not take into account the additional rainfall within the public right-of-way adjoining the street. This additional rainfall could provide additional water for the trees in drought years, and/or supply water needs of additional plantings such as shrubs or groundcover plants.

The rain and runoff can be harvested by mulched street-side basins at least 6 inches (15 cm) deep, 6 feet (1.8 m) wide, and 10 feet (3 m) long, in which the trees are planted. If the street has curbs, curb cuts may be needed to access the runoff. See box 2.2 for calculating basin capacities.

For every *inch* of rainfall…

A 10-foot wide paved street will drain 27,800 gallons of runoff per mile
A 20-foot wide paved street will drain 55,700 gallons of runoff per mile
A 30-foot wide paved street will drain 83,500 gallons of runoff per mile

For every *25 mm* of rainfall…

A 3-m wide paved street will drain 75,000 liters of runoff per kilometer
A 6-m wide paved street will drain 150,000 liters of runoff per kilometer
A 9-m wide paved street will drain 225,000 liters of runoff per kilometer

Rodd and I banned cars from the right-of-way with well-placed boulders and delineated a curving earthen footpath. I sold my car and fitted my bicycle with a large basket and saddlebags. Rodd parked his truck on the street. To shade pedestrians, bicyclists, and cars, we organized our neighborhood's first annual tree-planting event, planting 280 trees, 19 in the right-of-way adjoining our property.

We selected low-water-use natives including the velvet mesquite with its sweet-tasting seedpods, the desert ironwood with peanut-flavored seeds, and blue and foothills palo verdes with edible flowers and seeds.

We also planted water. We called 811 to mark existing underground utility lines for free (call your local utility for a similar service), and applied for a city permit to allow us to plant in the right-of-way. A city traffic engineer came by to ensure our earthwork and tree locations met standard setback requirements from utilities and did not block footpaths or views of stop signs. Infiltration basins and trees were positioned along the curb to shade the right-of-way and street. Dirt from the sunken basins was used to build up raised footpaths in the yard. Rain falling on the right-of-way now flows into infiltration basins where it waters trees. The land has been made pervious and is no longer compacted (compare figs. 8.30A and 8.30B).

Fig. 8.30A. Public right-of-way 1994, Tucson, Arizona

Fig. 8.30B. Public right-of-way 2006, Tucson, Arizona

We wanted rainwater to be the trees' primary water source during their establishment and the only water source when they matured. So we figured out our rainwater budget. With 12 inches (305 mm) of average annual precipitation, the microcatchments serving our infiltration basins could harvest 29,700 gallons (112,266 liters) of rain a year—enough to sustain the vegetation, but not to grow it to the desired size. For our 19 trees to reach a desired mature height of 20 feet (6 m) they would each need 3,000 gallons (11,349 liters) of water per year (see Volume 1, appendix 4 for Example Plant Lists and Water Requirement Calculations).[52] We would need another 27,000 gallons (102,060 liters), so we turned to the street and found the water we needed and more!

Our street is crowned (raised) in the middle so water drains toward the curbs where it concentrates and flows when it rains (box 8.3). Using the following, we calculated that our part of the street's catchment area would yield about 30,000 gallons (113,400 liters) of water per year:

Our part of the street's catchment surface was 19 feet wide × 256 feet long, which, when multiplied by 1 foot annual rainfall = 4,864 cubic feet of water. To convert cubic feet to gallons and take into account the runoff coefficient for the

street, we multiplied 4,864 cubic feet × 7.48 gallons/cubic foot × 85% runoff = 30,000 gallons (113,400 liters), street runoff available to our section of public right-of-way each year. (The 85% runoff coefficient is the estimated net water runoff from pavement; the other 15% is lost to infiltration, evaporation, etc. See appendix 2, equation 5.)

We directed street runoff into street side infiltration basins via curb cuts, and mulched the basins to increase water infiltration and help delineate the basins from the footpath (fig. 8.31).

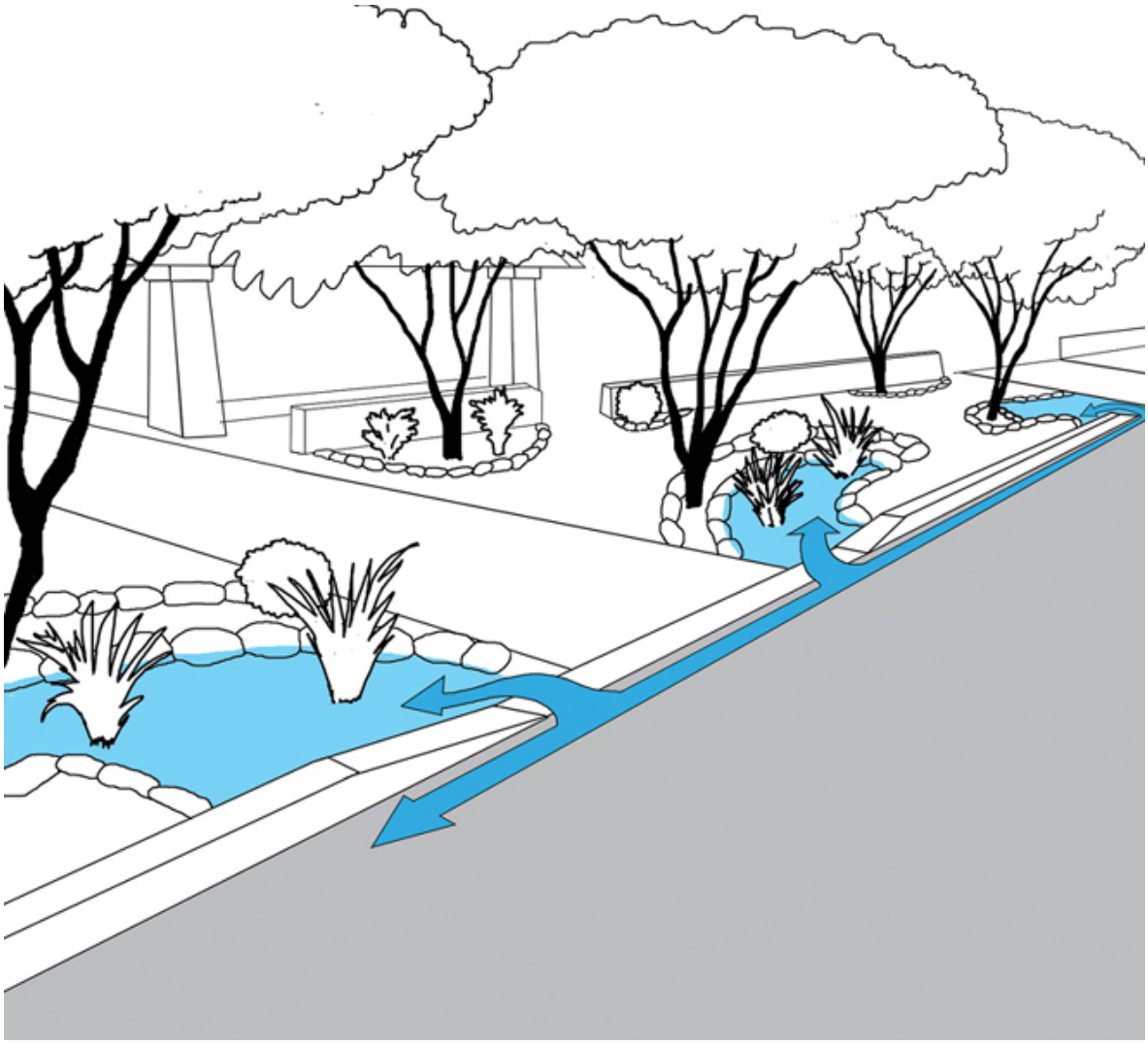


Fig. 8.31. Basins extend to existing driveway curb cut. Surplus water continues down the street after basins fill with water.

When the basins reach capacity, water backs up into the street, preventing additional street runoff from entering the system. Mulch floats up on the rising

water then settles back down as the moisture sinks into the earth. Our raised footpath acts as a dike keeping street runoff from flooding our property.

We could have stopped supplemental watering after three years, but we continued monthly watering in summer for another three years to increase the trees' growth, and then slowly weaned them from supplemental water. Today the trees arch over our heads, and water-harvesting earthworks are their prime water source providing 95% of the irrigation needs—we apply supplemental water only in extreme drought.

The vegetated right-of-way shades and cools the street and path. Runoff from the right-of-way now drains into the mulched basins, and there have been no ill effects to the plants from the pollutants collected with the stormwater. Life abounds where before there was none. (Compare figs. 8.32A, B, and C.)

Fig. 8.32A. Before. Public right-of-way 1994. This is the same right-of-way as in fig. 8.30A, but photographed from across the street.
Note: big exotic trees in background (neighbors' yards) did not receive harvested run off, and all died later of drought stress.

Fig. 8.32B. After. Public right-of-way 2004, with old driveway curb cut entrances. This is the same right-of-way as in fig. 8.30B, but photographed from across the street.

Fig. 8.32C. Public right-of-way 2014 post-curb cuts. Street runoff irrigates street trees via curb cuts and in-street water-harvesting chicane by yield sign. Blue arrows denote stormwater flow.

Box 8.4. How to Cut Curbs and Harvest Street Runoff

The strategy described below reduces street flooding, decreases the need for flood-control infrastructure, beautifies neighborhoods, creates wildlife habitat, and naturally filters pollutants from soil and air. Use this information as a template for creating curb cuts (fig. 8.33) where they are legal, or as the basis for obtaining an experimental permit.

Siting

1. Observe the flow of street runoff during a heavy downpour.

Note the flow's direction, location (in the middle of the street or along the curb), speed, volume, and the size of the watershed contributing runoff to the flow. Consider curb cuts only in locations where the following conditions exist: a) water flows along the curb, b) you are confident you can manage the flow, and c) there is sufficient space to harvest water in the public right-of-way—typically you need *at least* 4 feet (1.2 m) between the sidewalk/path and curb. Do not make curb cuts where water regularly goes over the tops of the curb, or where the street slope is steep, resulting in a very fast flow.

2. Check for the location of existing utilities.

Call 811 or a similar service to mark underground utility locations. Contact the landscape architect in your municipal traffic engineering department to find out the set-backs required from utilities, curbs, walkways, and traffic signs when digging and planting trees.

3. Mark infiltration basin locations.

Take into account required utility and traffic-sign setbacks and the locations where shade trees can shade both the street and footpaths, yet not block traffic signs or pedestrian view of oncoming cars.

4. Maintain pedestrian access.

Connect the street to the right-of-way via sidewalks or pathways constructed between basins. These accessways should be at least 4 feet (1.2 m) wide (though 5 feet [1.5 m] is better so two people can easily walk side by side) and at the same elevation as the top of the curb. Space the accessways an average of one car length apart from each another so that cars parked along the curb can open their doors to the paths— not dense vegetation in basins.

5. Dig your water-harvesting infiltration basins.

Leave a flat, compacted minimum 24-inch-wide (60-cm) platform of earth running along the right-ofway side of the curb for people to step onto as they exit vehicles parked along the curb (some folks may not think to park with their car doors accessing a path rather than a basin). This platform of earth should be level with the top of the curb. This earthen platform also ensures the deepest section of the basin is at least 24 inches (60 cm) away from the curb, lessening the chances of roots heaving the curb. Near walkways and the street, any slopes

you create should not exceed a 3:1 grade, unless delineated and stabilized with rock, while not exceeding a single drop of 20 inches (50 cm). Planting terraces can reduce single drops along paths while further delineating path from basin with terrace plantings (figs 8.33-8.34, 8.43-8.45).

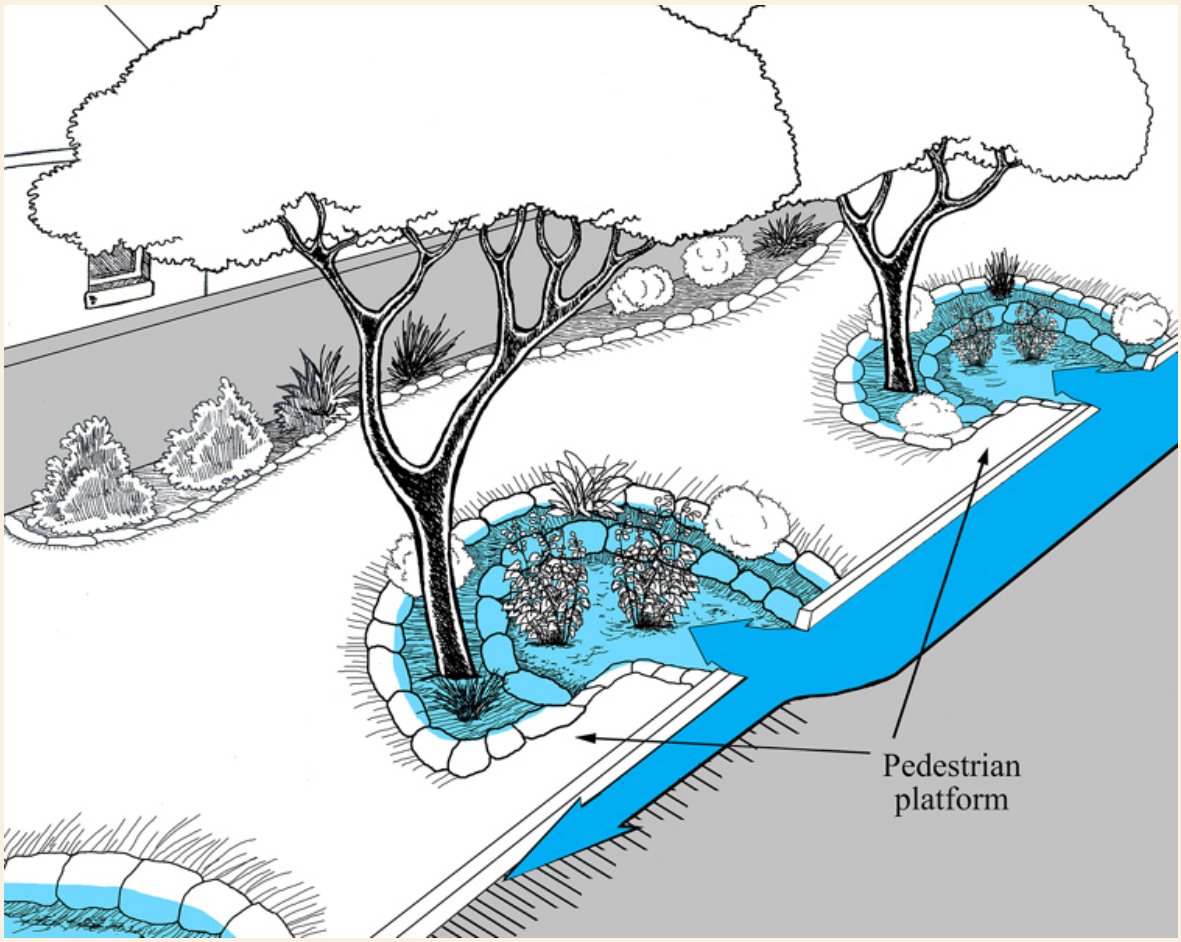


Fig. 8.33. Curb cut placed on the *up*stream side of basin to increase basin capacity. Street runoff enters basins via curb cuts. Once the *backwater* basins are full, surplus water continues down the street. Minimum two-foot (0.6-m)-wide pedestrian platform along curb makes it easier for passengers to exit cars parallel parked on street. Paths surrounding the basin are ideally no more than 2 inches (5 cm) above height of street curb. Higher path elevations would make basins appear deeper to pedestrians, without any actual increase in basin water-harvesting capacity because true basin depth is the elevation difference between curb cut inlet/outlet and bottom of basin—not the top of path.

6. Mark curb cut locations.

Place one curb cut per basin or per series of interconnected backwater basins, so surplus water will back up to the same place where it enters. This way, water

will pool and infiltrate *into* the basins, rather than erosively running *through* them. Locate the curb cut on the upstream side of your basin to increase water storage capacity. The curb cuts should be angled 45˚ on either side for safer, more gradual edges. Some concrete cutting services may have to make 30˚ cuts due to the limitations of their equipment. Make the base of the cut no wider than 18 inches (45 cm)—you want to let water in, not cars.

APPLY FOR A CURB-CUT PERMIT

Call your local transportation department officials to inquire about their public right-of-way curb-cut permitting process. This may require a couple of drawings describing what you intend to do (figs. 8.34A, B). Note: See "Street-Runoff Harvesting" page at HarvestingRainwater.com for additional curb-cut details.

Make the cuts

I recommend that novices make only one curb cut to start. See how it works in the next big rain, and if all is well you can make the rest of the cuts. If things go wrong—fix them and reconsider your plan to make more cuts.

7. **Call a concrete-cutting service** (about $300 for one complete curb cut, though the per-cut cost drops significantly with more cuts, since much of the cost covers getting the equipment and operator to and from the site) **or, if allowed, rent a concrete-cutting circular saw with minimum 14-inch (35-cm) diameter blade along with an industrial hand-held grinder*** (about $200 per day)**,** and search "Do-It-Yourself Curb-Cut Guide" at HarvestingRainwater.com.

Curb Cut & Curb Core Costs

*While some communities may allow citizens to make their own permitted curb cuts, mine currently does not. Instead, our transportation department requires licensed contractors/concrete-cutting companies to make the cuts. Thus, the rest of the steps apply to a licensed concrete-cutting company making the cuts.

A note on cost: You can determine a rough estimate of the stormwater-holding capacity of infiltration basins fed by curb cuts using the calculations in box 2.2 of chapter 2, and equation 8 in the calculations appendix. You can also estimate a $-per-gallon or $-per-liter cost for your basins and curb cuts with equation 9

in the calculations appendix. The two basins and curb cuts permitted with the drawings in figs. 8.34A, B each have a minimum *annual* stormwater capacity of about 5,000 gallons (19,000 liters) per year (in Tucson, AZ with an average annual rainfall of 12 inches or 305 mm), and a rough cost of $0.09 per gallon ($0.02 per liter) for the first year's stormwater capacity—a great deal especially since these earthworks and their vegetation also contribute to flood control; passive summer cooling; neighborhood beautification; local food production; improved air, soil, and stormwater quality; wildlife-habitat enhancement and more! (I saved on labor as I did much of the work myself, and now the plants and other soil life do the work increasing basins' capacity over time as their roots and hyphae grow, aerate the soil, and increase water infiltration rates).

8. Cut the curb.

Measure and mark all cut lines before the concrete-cutting service arrives. Ensure the street is clear for the large equipment (fig. 8.35A). And be on hand to observe and document the cutting service's quality of work (fig. 8.35B). After cutting, a good company will smooth out the cuts and their edges with a concrete grinder for a nicer appearance (fig. 8.36).

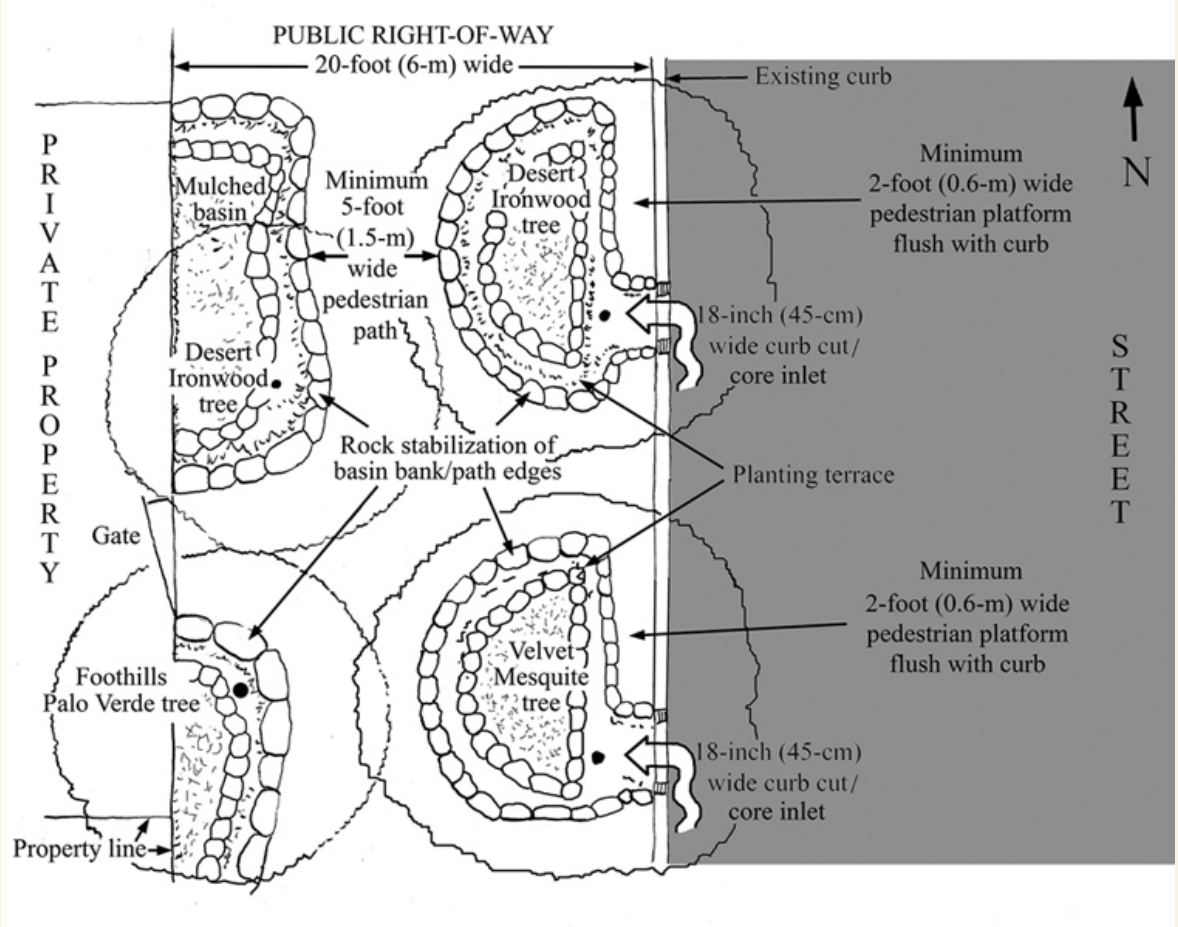


Fig. 8.34A. Have a minimum 2-inch (5-cm) drop from curb cut inlet to soil to increase water flow velocity and reduce the chance of a dam of sediment forming at inlet.

9. Make sure your basin bottom is lower than your curb cut inlet.

Make the bottom of the infiltration basin lower than the level of the street so water flows into the basin. Have a minimum 2-inch (5-cm) drop from curb cut inlet to soil to increase water flow velocity and reduce the chance of a dam of sediment forming at inlet (8.34B). Make sure the non-curb edge of the basin and associated path is the same elevation as, or no more than 2 inches (5 cm) higher than, the top of the street curb. This forces excess water to flow back to the street, not into the adjoining property where it could create flooding problems.

If the top edge of a basin is an earthen path, compact it to the desired elevation.

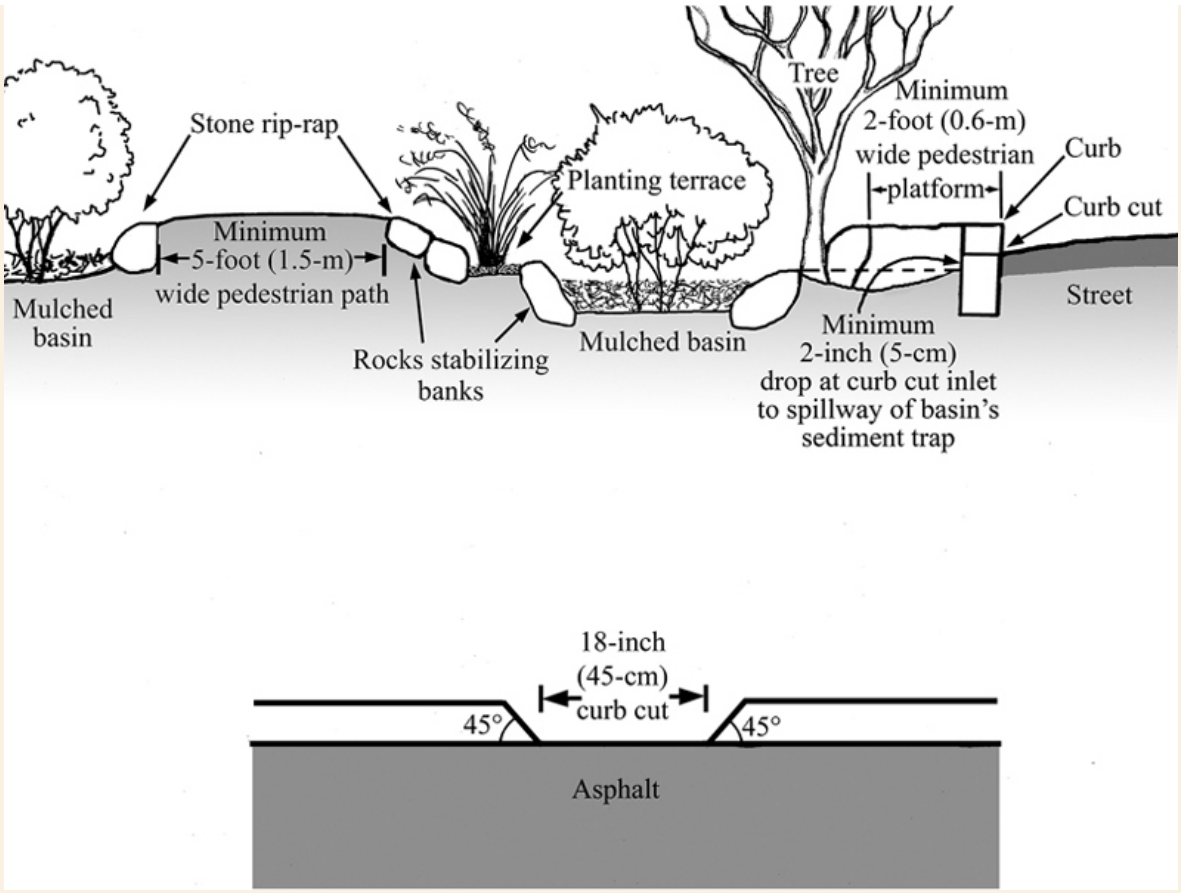


Fig. 8.34B. Curb-cut detail drawing for curb-cutting permit, elevation views. See the Street-Runoff Harvesting page at HarvestingRainwater.com for more details.

Fig. 8.35A. Concrete-cutting service beginning to make the horizontal cut of the curb cut

10. Plant a tree with each infiltration basin.

Plant trees 2-3 feet (60-90 cm) in from the curb, to keep them clear of cars, and to allow shade to be cast over both the street and footpath. The tops of your trees' root balls should be set at the level of the street-curb gutter/curb-cut inlet. If there is sufficient space in the basin, deepen the basin around the trees outside the perimeter of the root ball, leaving the trees on a slight pedestal or terrace inside the basin. This will help prevent the base of your trees from getting too saturated with water (see chapter 11 on vegetation for more details on tree planting).

11. Mulch your basins.

Organic mulch such as wood chips or compost distinguishes your basins from paths, reducing the chance of people walking through them. I prefer wood chips since the larger size lasts longer than smaller particle mulch. The mulch helps partially fill the basins with porous material, reducing the severity of their slopes, while increasing the rate that water infiltrates into the soil. In addition, the mulch creates habitat for soil microorganisms that bioremediate toxins in water

running off the street. Keep mulch well below the curb cut inlet elevation so it won't block the inlet. See fig. 8.37 for finished curb cuts and basins.

Fig. 8.35B. Concrete-cutting service making an angled cut

Fig. 8.36. Smoothing out the cuts and edges with an industrial hand-held grinder

Note 1: See figs. 8.26B, C for a flush curb that spreads rather than concentrates runoff, making street-side water harvesting easier while eliminating the need for curb cuts.

Note 2: Larger, wider, pedestrian-oriented, water-harvesting, tree-lined public rights-of-way should become the standard in urban and suburban environments to offset the mass paving of the watershed and shrinking yard sizes. As private outdoor space shrinks, public outdoor space must increase. Place underground utilities in the street instead of in the public right-of-way so more trees and understory vegetation can be planted to utilize the harvested runoff without utility conflicts. See Terraced Cistern Steps, Gardens, and More in the Real-Life Examples section of chapter 4 for an example of a dynamic urban right-of-way.

Fig. 8.37A. The finished curb cuts, basins, and trees in 2007. Work was permitted with drawing similar to figs. 8.34A, B.

Fig. 8.37B. Curb cuts, basins, trees, and understory vegetation in 2015. Established plants only watered with direct rainfall and street runoff.

Box 8.5. Curb Cores

Curb cores cost less than curb cuts (figs 8.38 - 8.41), but since their openings are smaller than a curb cut's they are more likely to clog with debris, and in a short intense storm street-gutter flow may cease before basin fills with water flowing through curb core.

Maintenance practice for both curb cores and curb cuts entails inspection and clean out before and after storms (or more fun—*during* storms).

For costs of curb cores and curb cuts, search "Street-Runoff Harvesting" at HarvestingRainwater.com.

Fig. 8.38. Coring curb with hand-held core drill. 4-inch (100-mm) core hole (or if possible—bigger) is typically best, but sometimes 3-inch (75-mm) is needed because the City of Tucson requires a minimum of 2 inches (50 mm) of solid curb above the curb core hole. Angle of core cut should be steeper than street-gutter slope to reduce the chance of slowing water flow and clogging core with sediment.

Fig. 8.39. Finished core. View from inside of curb. Note that it is best to have a minimum 2-inch (50-mm) drop from bottom of curb core to top of mulch within basin to reduce the chance of the core cut clogging with sediment.

Fig. 8.40. A 4-inch (10-cm) core drilled through the street curb to direct street runoff to a street-side garden of native vegetation. Photo taken 8 months after installation and planting of what were 1-gallon (3.8-liter) pot-size plants.

Fig. 8.41. Note well-done curb core creates a cut dip in the curb gutter to direct more water through the core hole. Core is both sloped down to basin and angled in direction of street gutter flow.

Box 8.6. We Can Choose Between Public Commons That are Dead or Alive

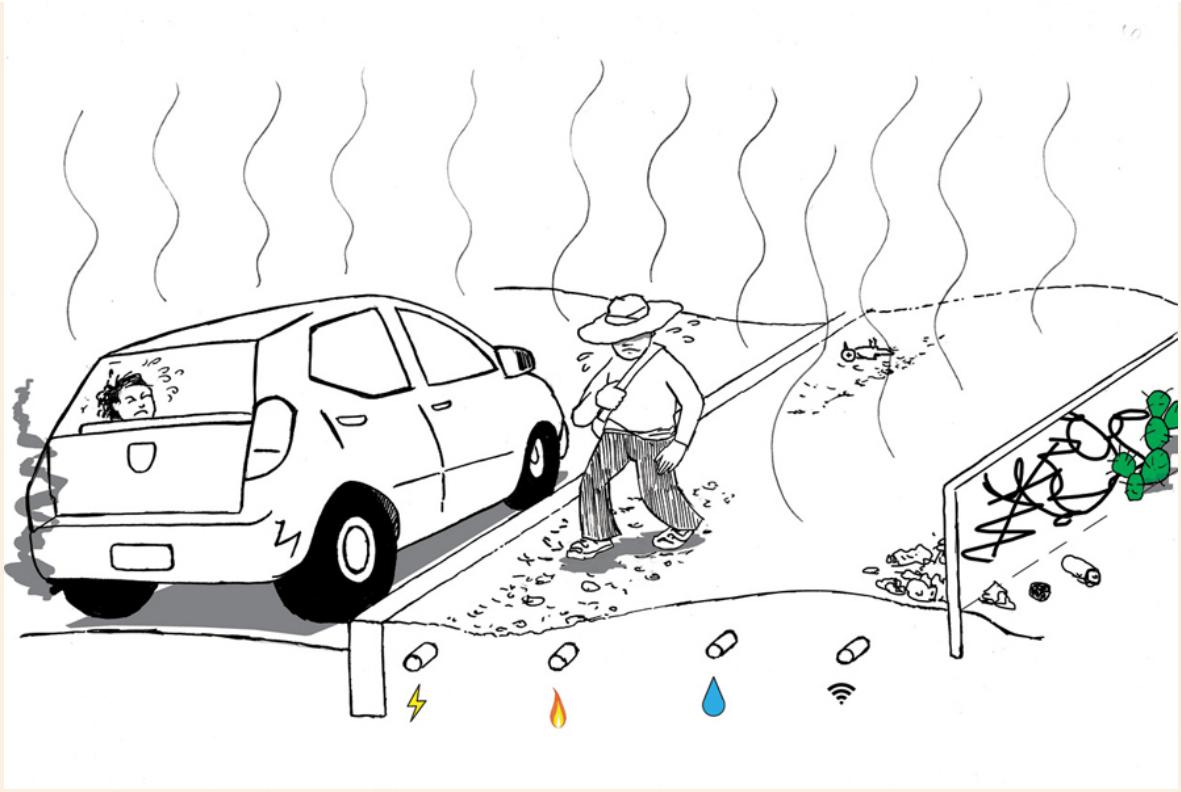


Fig. 8.42A. Dead. Poorly-placed underground utilities turn a public right-of-way into a degraded private-utilities right-of-way. Due to required setbacks from utility lines, no rainwater, stormwater, or trees can be planted here.

Fig. 8.42B. Alive. Well-placed underground utilities (placed either in the street or closer together, beneath earthen footpath, *away* from the street and its runoff) allow for a verdant public right-of-way. Rainwater and stormwater are planted in street-side basins. Trees are planted to utilize the runoff, filter it, and shade the maximum amount of street and walkway. This best practice is enabled by municipal policies identifying best stormwater- and tree-planting areas, then banning placement of utilities in these areas.

Box 8.7. *Backwater* or *Eddy* Basins

These basins are largely self-maintaining, thus they are typically my favorite—especially for do-it-yourselfers. As a backwater basin fills with water, the water gradually and calmly backs up to the basin's inflow point, and surplus water continues flowing down the pavement-stabilized street-curb gutter. When done right there are no erosion problems. These basins are ideal for mulched bottoms —do not put rock in an eddy basin's level bottom as it will impede the rapid

infiltration you desire. Mulch may float in basins, but for the most part will not leave; instead more will be gained—especially if inlets are at the upstream side of basins. Incoming water transports leaf drop from the street into basins.

Regenerate mulch as needed with leaf drop and cut-up prunings from the plants growing in the basin. The rate of decomposition of the biomass in the basins will be quicker than non-basin areas due to the increased water inputs, which leads to a nice balance. I've found that by the time plants are ready for another pruning, the basins are ready for another application of mulch from the basin's cut-up prunings.

KEY ELEVATION RELATIONSHIPS FOR BACKWATER OR EDDY BASINS

The upper edge of the farthest-downstream section of the basin (A) must be higher (ideally at least 4 inches [10 cm] higher) than the basin's curb-cut, or curb-core, inlet (B)(fig. 8.43).

If the upper edge of this downstream section of the basin (A) is lower than the inlet (B), the basin will act as a *flow-through* basin, not a backwater basin, as water will overflow at the downstream end (taking mulch with it) and, in this context, erode the earthen walkway. Thus, steeper streets will have shorter eddy basins (parallel with the street), while more-gradually sloping streets can have longer eddy basins.

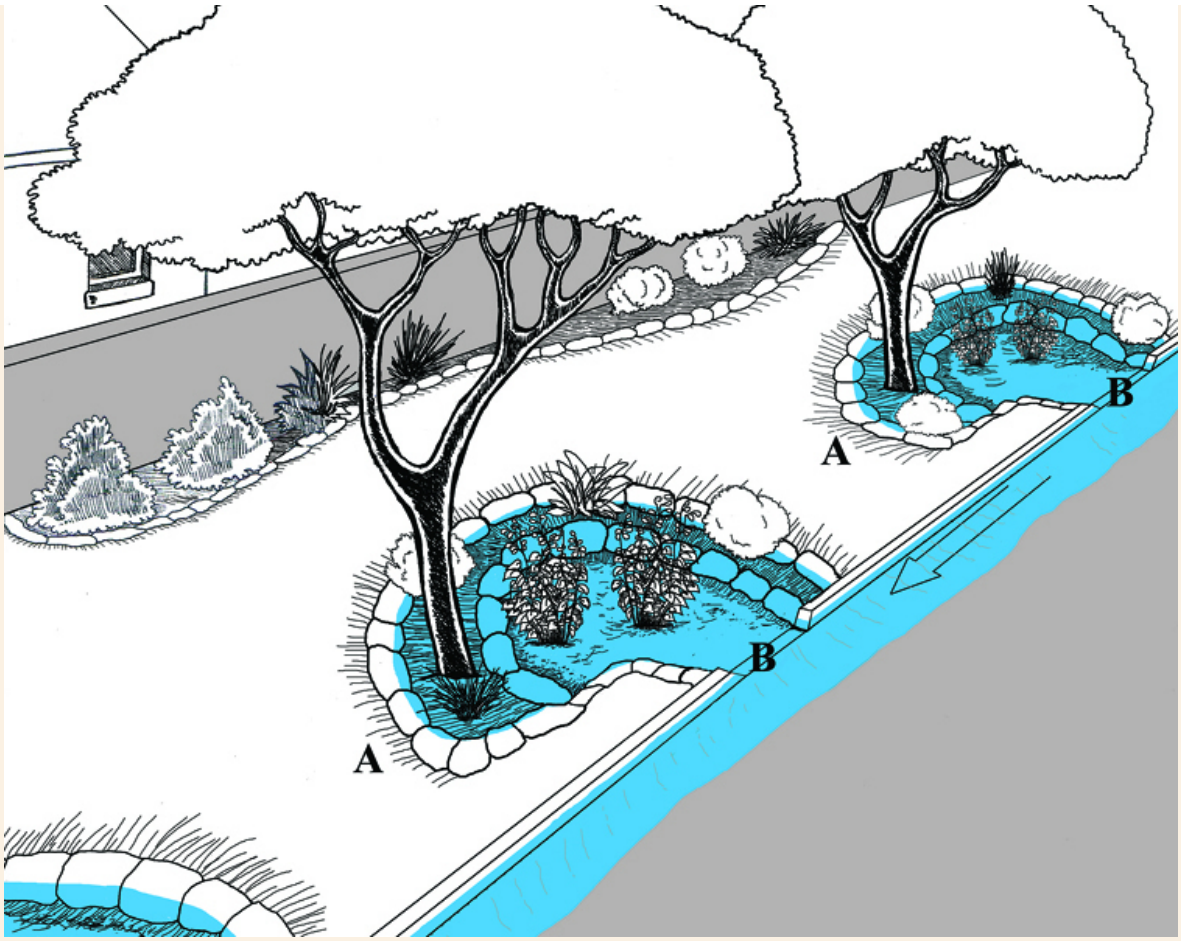


Fig. 8.43. *Eddy* or *backwater* basins. The upper edge of the farthest-downstream section of the basin (A) must be higher (ideally at least 4 inches [10 cm] higher) than the basin's curb-cut, or curb-core, inlet (B). Arrow denotes water flow. See laser level section of appendix 1 for how to measure these and other key elevation relationships.

Box 8.8. Important Elevation and Slope Relationships

Based on Tip 9 from Introduction and *erosion triangle* in chapter 1, part 1.

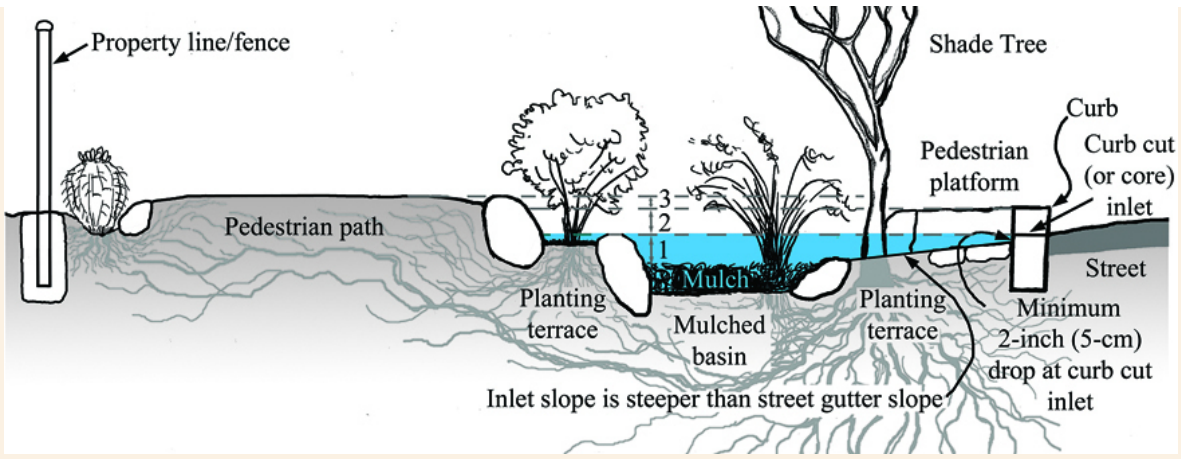


Fig. 8.44. Elevation view of curb cut and basin. Low water level just after storm.

***Elevation 1*: Bottom of basin, and the top of the mulch within it, is lower than elevation of curb-cut inlet so structure accepts and holds street runoff. The deeper the basin in relation to its inlet/overflow, the greater its water-holding capacity.**

***Elevation 2*: Curb-cut inlet is the low point of the basin's perimeter, so water will overflow at (or back up to) the inlet and the pavement-stabilized street-curb gutter. Planting terraces are higher than bottom of basin—but no higher than the curb cut inlet, for plants less water-tolerant than those planted in bottom of basins. Terraces also reduce the otherwise sudden drop along adjoining paths and pedestrian platforms.**

***Elevation 3*: Pathway elevation is level with, or no more than two inches (5 cm) higher than, top of street curb so pathway is at least 4 inches (10 cm) higher than inlet/overflow so water will not flow over path into adjoining properties. Additionally:**

• Minimum 2-inch (5-cm) drop at inlet; plus inlet slope is steeper than street curb gutter slope to speed up, rather than slow, flow of incoming water—so sediment in water won't drop out of flow and clog inlet. Note: Inlet slope can be stabilized with only one layer of rock. Rock more than one course high/deep is a waste of material and may impede germination of beneficial vegetation between rocks.

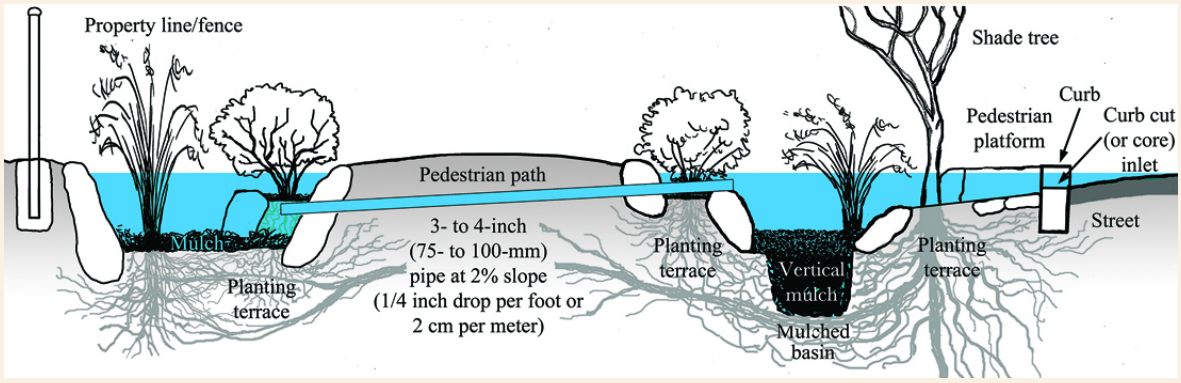


Fig. 8.45. Increasing street runoff-harvesting capacity within wider public right-of-way with vertical mulch and a pipe moving water to other side of footpath. High water level during storm. Vertical mulching (see Mulching chapter) increases water-holding capacity without increasing the depth of surface water—water will fill the coarse mulch packed into the mulch pit, but a person could stand on the mulch without sinking. Cut-up prunings, leaf, and seed drop from the street tree make the best, free, on-site mulch. Mulch is regenerated with every pruning. Pipe can move water from street-side basin, under path, to property-side basin. Bottom of pipe at inlet should be about one inch (25 mm) below curb cut inlet elevation. This can work especially well when underground utilities limit the size of street-side basin. Path is best placed *over* underground utilities.

Box 8.9. Small-space Backwater or Eddy Basins

Sometimes a site's constraints, such as a narrow planting strip between the sidewalk and the street curb, allow for only small eddy basins. In very urban settings such basins are sometimes completely surrounded by sidewalk, and may have a metal tree grate, level with the top of the sidewalk, around the tree (figs. 8.46A, B). Larger basins with greater water-harvesting capacity would be more advantageous for the associated trees and soil life, but something is better than nothing. Such basins without subsurface drains are not recommended in areas with expansive clay soils where the drying and wetting of the clay could lead to cracks in sidewalk and curb.

No pedestrian platform is needed if the basin is only as wide as the curb cut—especially since the tree (and understory plantings if present) will act as a pedestrian barrier (figs. 8.47A, B).

Nor are pedestrian platforms needed if there is no on-street parking (fig. 8.28).

Some municipalities require a 1-foot (30-cm)-wide level buffer alongside the sidewalk. Where that is not required, the basin, and the rocks stabilizing its bank, can go right up to the sidewalk, and act as a visually-impaired-friendly raised curb to the basin if they rise 4 inches (10 cm) above the sidewalk (see fig. 8.28 for a basin's raised concrete curb).

In such locations a more water-tolerant tree is used, since it will not be planted on a platform or terrace.

Fig. 8.46A. Small-space eddy basin with steel grate above basin, downtown Tucson, Arizona.
Desert willow (*Chilopsis linearis*) tree

Fig. 8.46B. Close up of curb cut to small eddy basin with steel grate around tree.
Designed by Tucson Department of Transportation

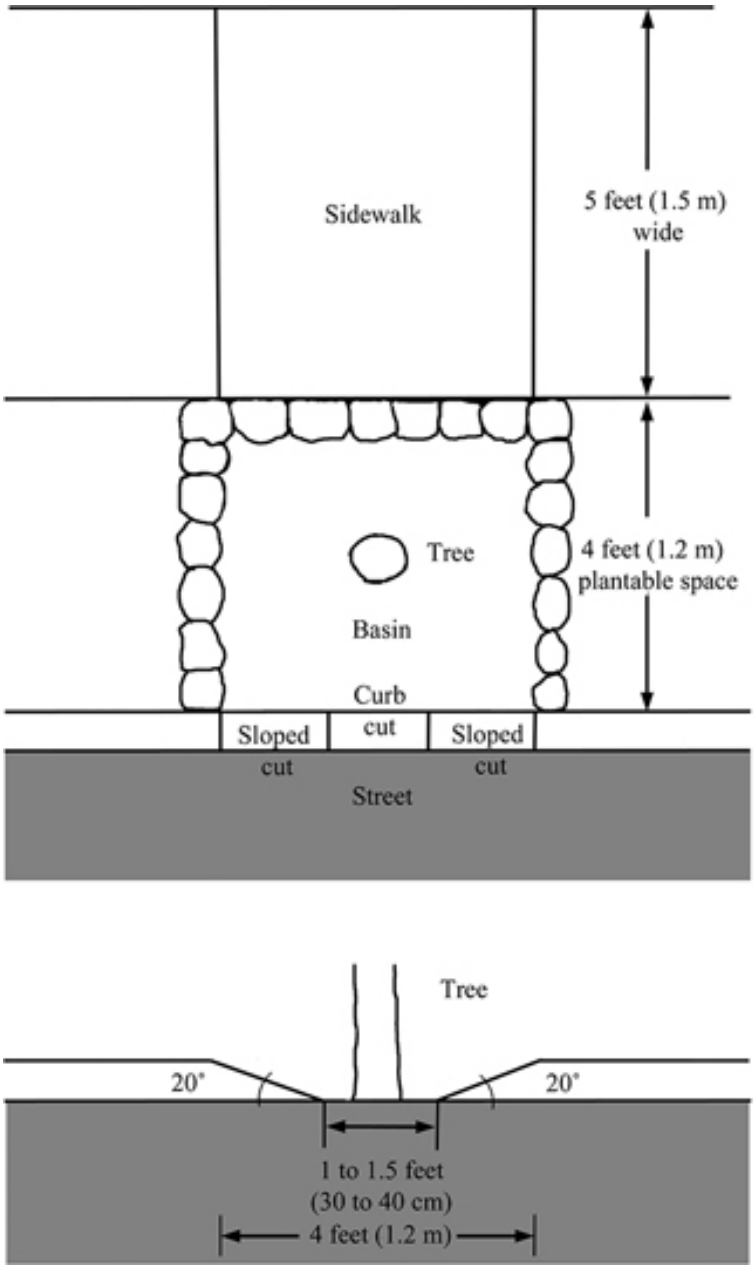


Fig. 8.47A. Small-space eddy basin with *no* steel grate around tree. Plan view above. Elevation view below. Basin without pedestrian platforms could be longer along the street if there were no on-street parking.

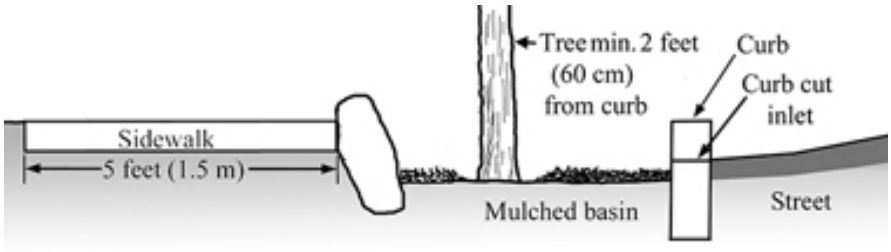


Fig. 8.47B. Small-space backwater basin, elevation view. Bank-stablizing rock rises four inches (10-cm) above sidewalk to create a raised curb for those on wheels and the visually impaired using canes.

TIPS TO MAKE PUBLIC RIGHT-OF-WAY WATER-HARVESTING BASINS SAFER FOR PEDESTRIANS

Corresponding with the cities of Tucson, Arizona; New York City; and Portland, Oregon; which have been implementing street-side and in-street water harvesting basins for years, Water LA learned that as of September 2015, Tucson and New York had no complaints of anyone tripping on or falling into a water-harvesting basin. Portland had only one.[53]

Design strategies to reduce a potential fall can include:

Create or grow visual/tactile indicators

• Grow vegetation within the basins—understory plantings as well as trees.

• Mulch the basins.

If path is also mulched, use a different type of mulch for each context, such as a screened mulch of material 3 inches (75 mm) or smaller in size for the path, while using more coarse cut-up prunings within the basin.

• Outline basin with rock, urbanite, a solid curb, or vegetation.

The greater the difference in lightness or darkness between the footpath, the basin, and or the material outlining the basin's boundary, the better for night use. For example, dark mulched basins outlined with light-colored rock along a dark mulched footpath stand out more clearly at night.

A 4-inch (10-cm) high curb around basins is the recommended minimum height for cane use by the visually impaired (figs. 8.27, 8.28). Note: 4-inch (10-cm) cuts can be made in such a curb to allow path runoff to drain into the curbed basins. Rock and/or vegetation can also work as a raised curb.

Make obvious, convenient pathways

• Construct footpaths to a minimum 5-foot (150-cm) width, so two people can easily walk side by side. Keep path clear of vegetation to minimum 5-foot (150-cm) width and a minimum height of 7 feet (215 cm).

Make more gentle transitions

• Make curb cuts' side cuts at a 45˚ angle, rather than vertical

• Where there is on-street parking, set basins back 2 feet (60 cm) from curb to create a level platform even with the top of the curb, which people can step out onto when exiting cars parked along the curb.

When there is no on-street parking, bring the basin all the way over to the curb to maximize water capacity.

• Implement a 3:1 side slope down into the basin— this slope is intended to be gentle, starting with a 1- to 2-inch (25- to 50-mm) drop down from the sidewalk/footpath to ensure drainage (figs. 2.1, 2.11). Where there is not enough space for such gentle slopes, planting terraces or curbs may need to be considered.

• Include a 12-inch (30-cm) wide flat area next to the sidewalk, and then a 3:1 side slope down into the basin—a variation on the above that provides more of a buffer along the footpath (fig. 2.11).

• Use flat curbs, flush/level with the street. No curb cuts are needed as runoff flows as calm, shallow, spread-out sheet flow off the street, or parking lot (*wheel stops* or *parking stops* keep parking cars from driving over curb), over the flat curb, and into the adjoining basin (figs. 8.26B, C).

• Install planting terraces along basin's edge where it abuts footpaths/sidewalks to reduce sudden drop into the bottom of the basin (figs. 8.33, 11.12).

CITY POLICY TRANSFORMS DEHYDRATION STREETS INTO REHYDRATION STREETS

In 2013 the City of Tucson approved a Green Streets policy that requires new and reconstructed roadways be designed to harvest the first 1/2 inch (13 mm) of rainfall in a storm to grow vegetation street-side and in medians. Passive water-harvesting earthworks are the strategy of choice, as they quickly infiltrate the stormwater into the soil to freely irrigate trees and other vegetation shading the street's hardscape, walkways, and bicycle paths. The policy also requires a minimum 25% tree canopy cover and a minimum 25% shrub and grass cover in landscaped areas. (There is more than enough on-site storm-water to freely irrigate an increase in this required shade canopy, but this is a good start).

This is a dramatic 180˚ shift in how our streets and adjoining rights-of-ways are designed and built. In the past, *lifeless*, *grey* infrastructure of asphalt and concrete drained nearly 100% of the rainfall while generating higher summer temperatures due to the heat-island effect from all the exposed hardscape. Now *living*, *green*

infrastructure is being built and planted along and within the streets to harvest and reinvest nearly all the rainfall and street runoff from a typical storm to generate and grow living air conditioners and water/air/soil filters of beautiful, flood controlling shading vegetation.

For this to be realized, the city had to change how it deals with utility companies to ensure that their infrastructure (water, gas, and electric lines) would not be placed in locations ideal for the planting of stormwater and vegetation (figs. 8.42A and B). The city now meets monthly with the utility companies to go over all their roadway projects and explain what the city is trying to achieve with its green-streets strategies and goals. These meetings begin early in a project's design process and continue to the end of its implementation. Typically the utility companies are able to move their infrastructure as asked, but when that is not possible, the city and the utility companies brainstorm how they can work together to still realize the green-streets goals by modifying a green-streets strategy (e.g., by making a basin shallower and using shallower-rooted plants when above utility lines, or by moving rain gardens and their associated trees, stormwater inlets, and pathways to ensure stormwater is still infiltrated to grow the shade over the hardscape).

The implementation of this policy was due in part to a grant from the Arizona State Forestry Department along with an EPA grant that funded city staff to work with the local non-profit Watershed Management Group to create a green-infrastructure guide, the willingness of municipal staff and elected officials to change the status quo, and a rapidly growing segment of the city's population that was practicing water harvesting in their own lives and demanding the city do the same.

CHAPTER 9

Diversion Swales

WHAT IS A DIVERSION SWALE?

A diversion swale is a gently sloping drainageway that moves water slowly downslope across a landscape, while simultaneously allowing some of it to infiltrate into the soil. Like a berm 'n basin, it usually consists of a generally curvilinear basin with the excavated earth placed downslope to form a berm. Unlike a berm 'n basin, which is constructed on-contour to contain and allow all water to soak into the earth locally, a diversion swale is built *slightly* off-contour, allowing a portion of the water to soak into the soil locally while moving surplus water slowly downhill from one place to another, infiltrating water all along the way (fig. 9.1). A diversion swale is sometimes called a *diversion drain*,[1] with a variation known as a *spreader drain*. Landscape architects may refer to a diversion swale as a *bioswale*.

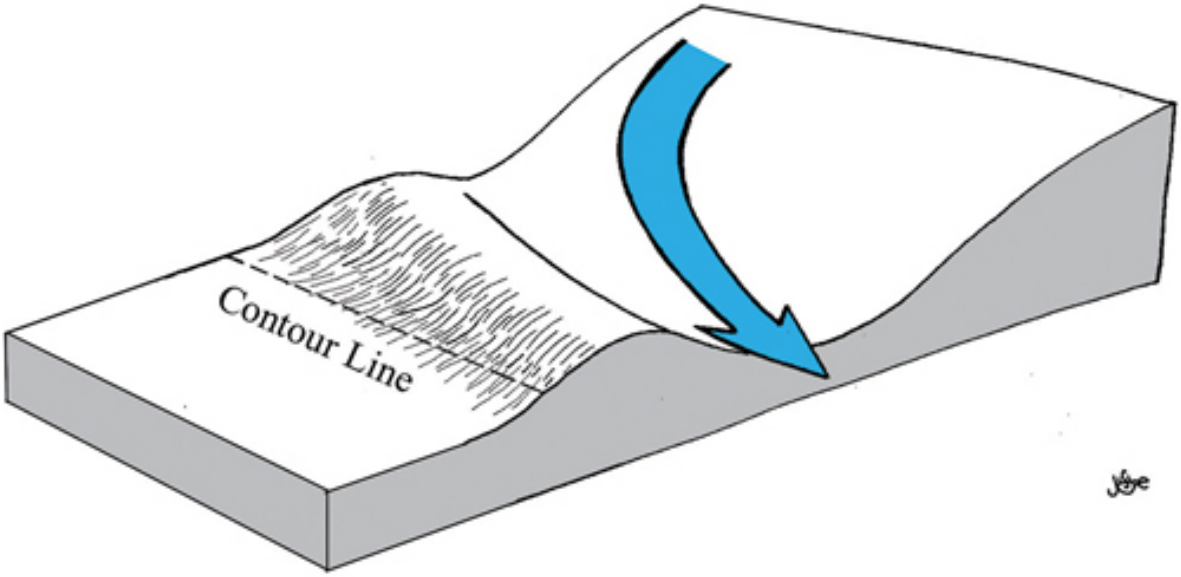


Fig. 9.1. Diversion swale

This chapter also discusses *ponds*, which can be the large "infiltration basin" or collection endpoint of diversion swales.

WHERE IS A DIVERSION SWALE USED?

Diversion swales are used to intercept, infiltrate and redirect both sheet flow and channelized water. Diversion swales can tame the force of water that rushes out from a culvert or roadside bar ditch, transforming the concentrated fast-moving water into a valuable resource by spreading out and calming the flow. Diversion swales can direct runoff to a water-harvesting berm 'n basin, infiltration basin, pond, or other final destination (fig. 9.2).

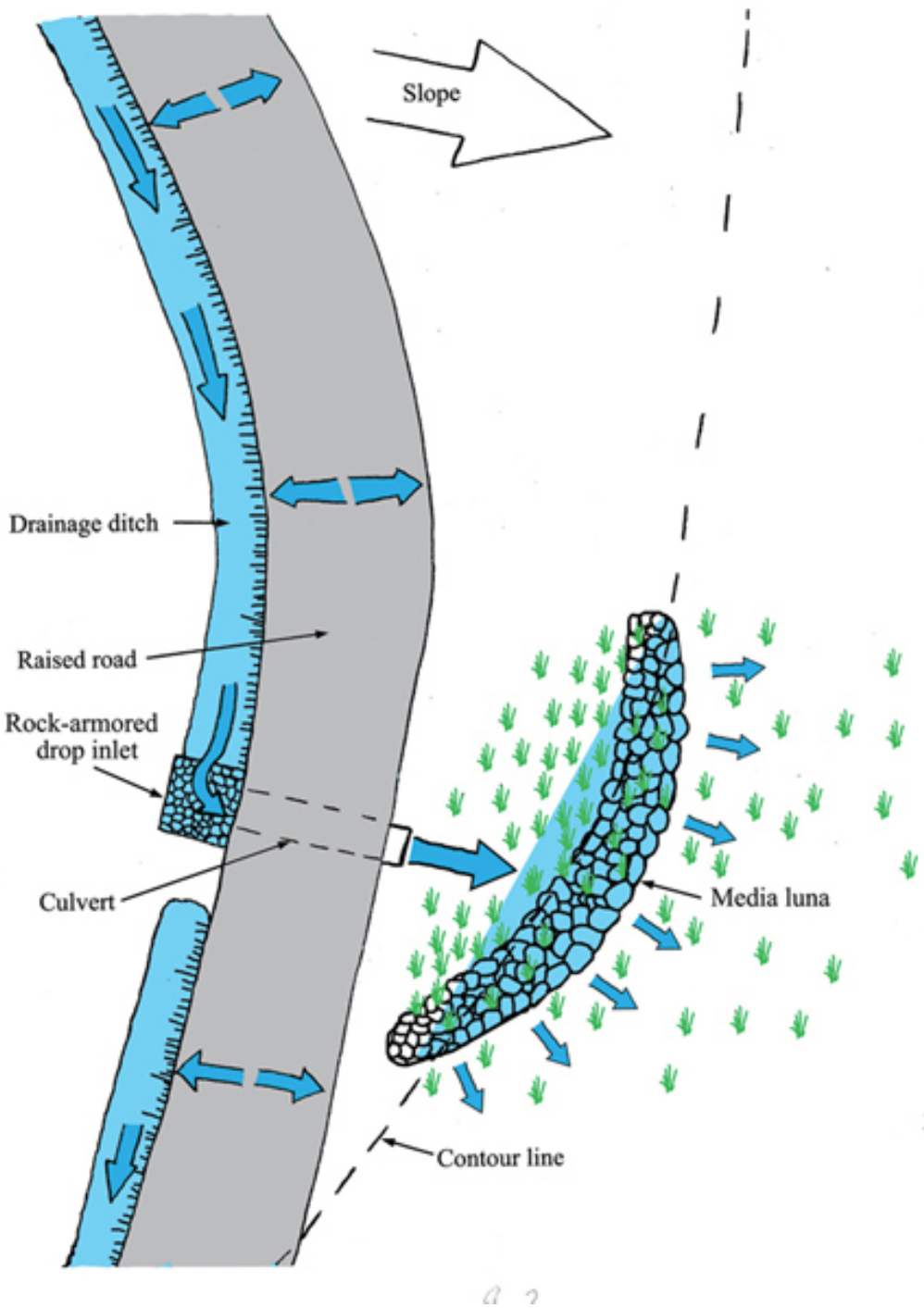


Fig. 9.2. A sheet flow spreader or media luna slowing, spreading, and sinking flow from a culvert to transform erosive channelized flow into productive sheet flow. Here the one-rock-high *sheet flow spreader* acts like a one-rock dam/diversion swale hybrid. See chapter 10 for more

Diversion swales can integrate multiple water-harvesting earthworks by diverting overflow water from one earthwork to another. For example, a series of diversion

swales can transport overflow from one infiltration basin to another until the final diversion swale directs remaining overflow to a natural drainage way (fig. 9.3). In agricultural irrigation applications, diversion swales can act as both water inlet channels and drain channels removing surplus water (fig.9.4).

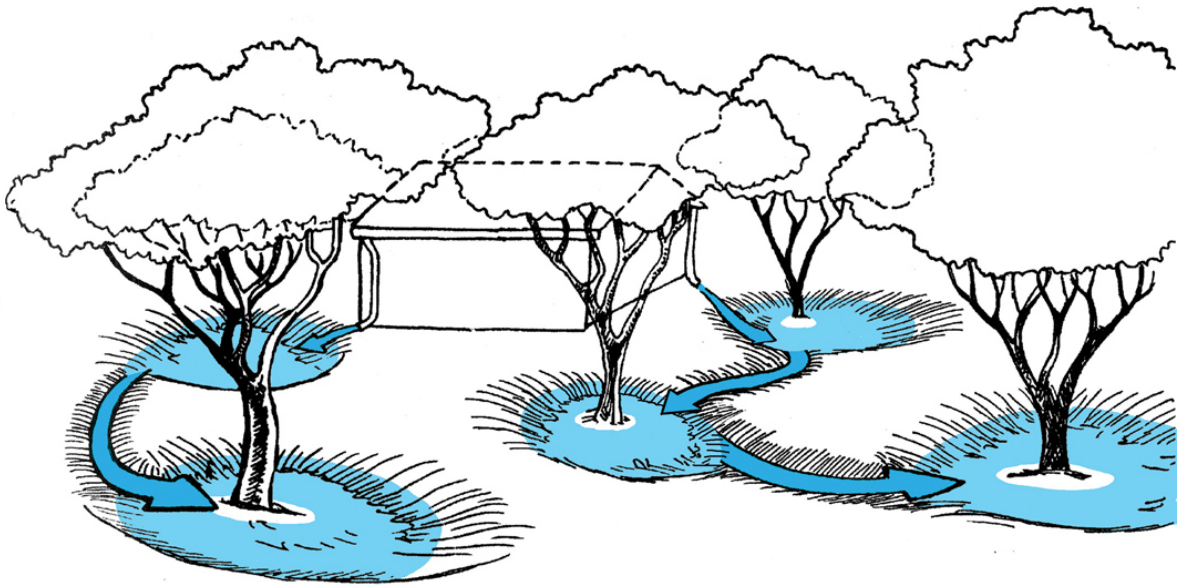


Fig. 9.3. Diversion swales as the overflow route from one basin to another

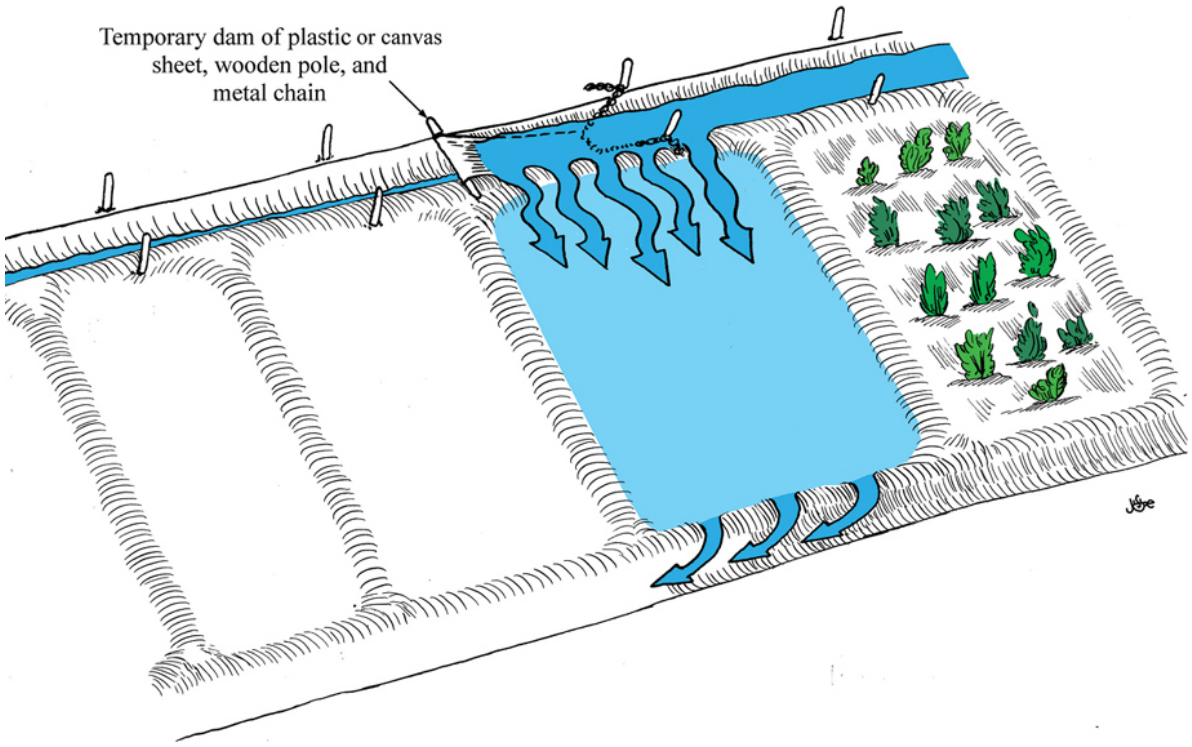


Fig. 9.4. Diversion swales used as inlet (head drain) and outlet (tail drain)channels for irrigation and overflow of agricultural fields

Diversion swales can be multifunctional. Their berms can function as raised roads or paths, as well as water-harvesting speed humps directing street runoff to vegetated basins. They can be used for beautifully landscaped stormwater control in developments, as well as to "daylight" formerly buried or culverted streams. The second Real-Life Example shows how a spreader drain harvests "unwanted" water from an upslope property to sustain a thriving windbreak of trees.

Diversion swales should not be used in situations where alkaline soils are prone to waterlogging and salt buildup.[2] Waterlogging occurs when soil moisture collects atop subsurface hardpan or clay layers, saturating the topmost layer of soil. The accumulating runoff introduces more salts to the soil, and the poor drainage keeps it around. In such instances, a combination of water-harvesting earthworks and *interceptor drains* may be needed to infiltrate rainfall higher in the watershed to reduce runoff, then drain excess runoff water from the site. See appendix 4 for more on interceptor drains.

TOOLS AND MATERIALS

Tools: You will need a bunyip water level (see appendix 1) or other surveying device, flagging or survey stakes, shovels, and pick axes. For large projects consider using a road grader, backhoe, or similar large machinery to do the earthmoving.

Materials: Seeds and/or live plants to vegetate the berm and spillway of your diversion swale.

IMPLEMENTATION STEPS TO BUILD A DIVERSION SWALE

SITING

Steep/erosional and gentle/depositional slopes

Carefully study the condition of the watershed. In landscapes with varied topography—especially undulating hills and valleys—identify these conditions:

- Flatter areas at the tops of hills, where both erosion and deposition is relatively small
- Steeper slopes, where more soil is lost through erosion than is gained by deposit
- Gentler slopes downhill from steeper slopes, where more sediment is deposited than is lost through erosion
- Transition points and lines between the areas above

On a micro-level, you may see a gradual slope that is covered with vegetation, organic matter, and silts, which then transitions to a steeper patch of naked sloping dirt, then changes back to a more gradual slope where vegetation, silts, and organic matter again accumulate (fig. 9.5). Areas with gradual slopes could be good locations for planting since they receive water and fertile organic matter and are not degrading. Gradual slopes lower in the landscape tend to have the best conditions for planting since these areas receive runoff from both the gradual and steep-sloped areas above.

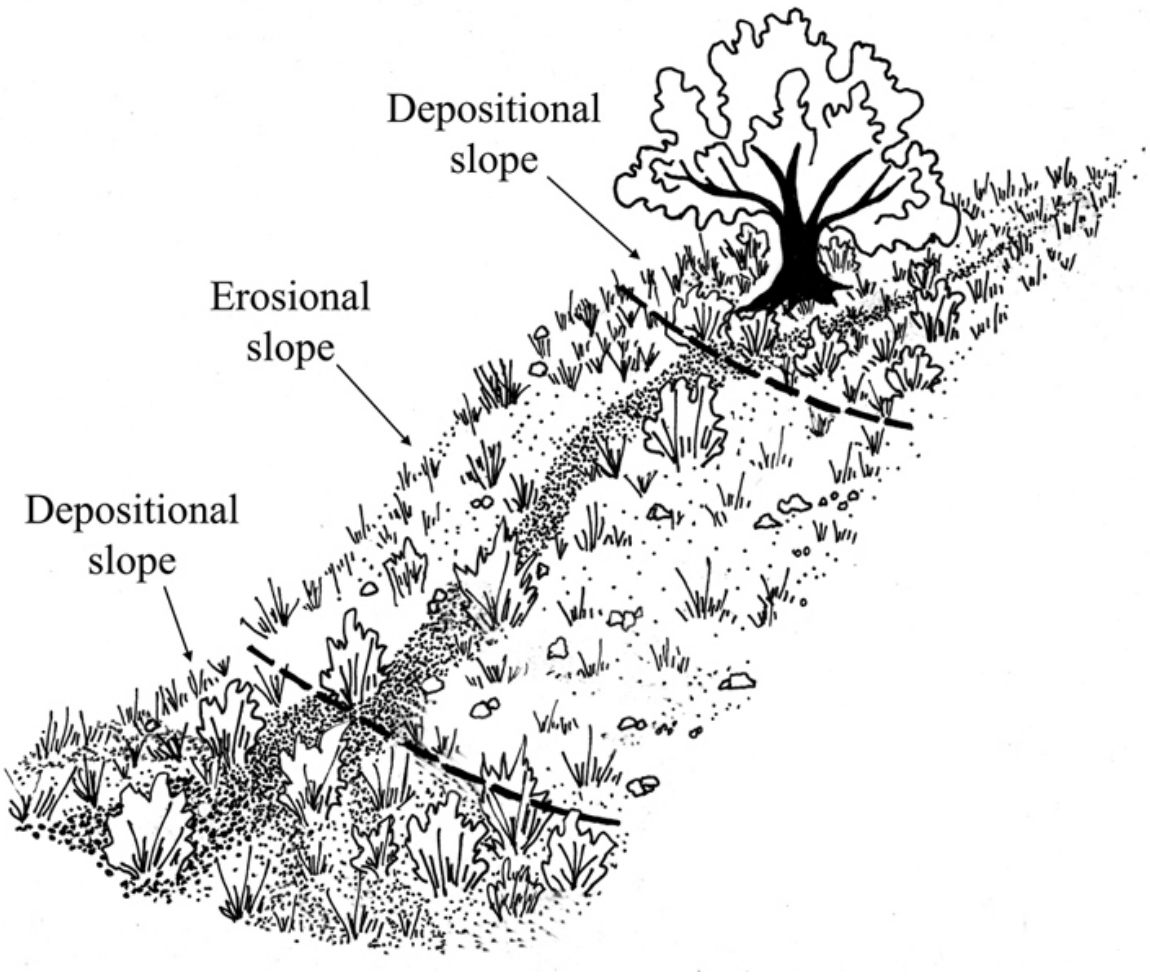


Fig. 9.5. Alternating gradual/depositional slopes and steep/erosional slope

On a macro-level, mountaintops and hilltops can transition between steep and more gradual slopes. Steeper slopes with substantial erosion can transition to more gradually-sloping areas where sediments are deposited to form alluvial fans.

Whether you are working at the micro-scale or macro-scale, concentrate water-harvesting and revegetation efforts in gradually sloping depositional areas where less effort is required. Working in a depositional area that is located above a steeper slope could help revegetate the steeper slope below as seed and moisture move downhill. But be very careful hydrating depositional areas located above steep slopes in regions prone to mudslides. In these areas, you may want to focus your water-harvesting efforts exclusively on depositional areas below—not above—steep slopes.

Diversion swales should only be used on depositional slopes where they are easier to build because less soil needs to be moved, they are more stable, and they

function more efficiently to divert surplus water from one location to another.

If you are building a small earthen dam or pond, make sure you will not back water up above the gradual/depositional slope or the keypoint. Keeping the water level below the steeper/erosional slopes allows you to direct overflow across gentler, more easily managed gradual/depositional slopes.

The path of the diversion swale

To lay out a diversion swale, stand where you'd like your swale to begin (at a water's source which you want to slow, spread, and sink—such as at a culvert's downstream opening or where unchecked runoff is about to become erosive), where you want the berm of the swale to act as a raised path, or where there are no conflicts with infrastructure or landforms (trees and rock outcroppings). Then mark off a contour line, using your preferred tool (see appendix 1), in the direction you want the swale to go. (Refer to fig. 9.6A). Every 25 to 100 feet (or every 10 to 30 meters) along the contour put a stake or flag in the ground to act as a distance marker (placing stakes at closer intervals enables you to use a bunyip water level with a shorter tube, and makes it easier to see subtleties in the slope of the landscape). The contour line will act as a reference point from which you will mark the slope of your diversion swale, and the distance markers will be where you will measure the drop in slope.

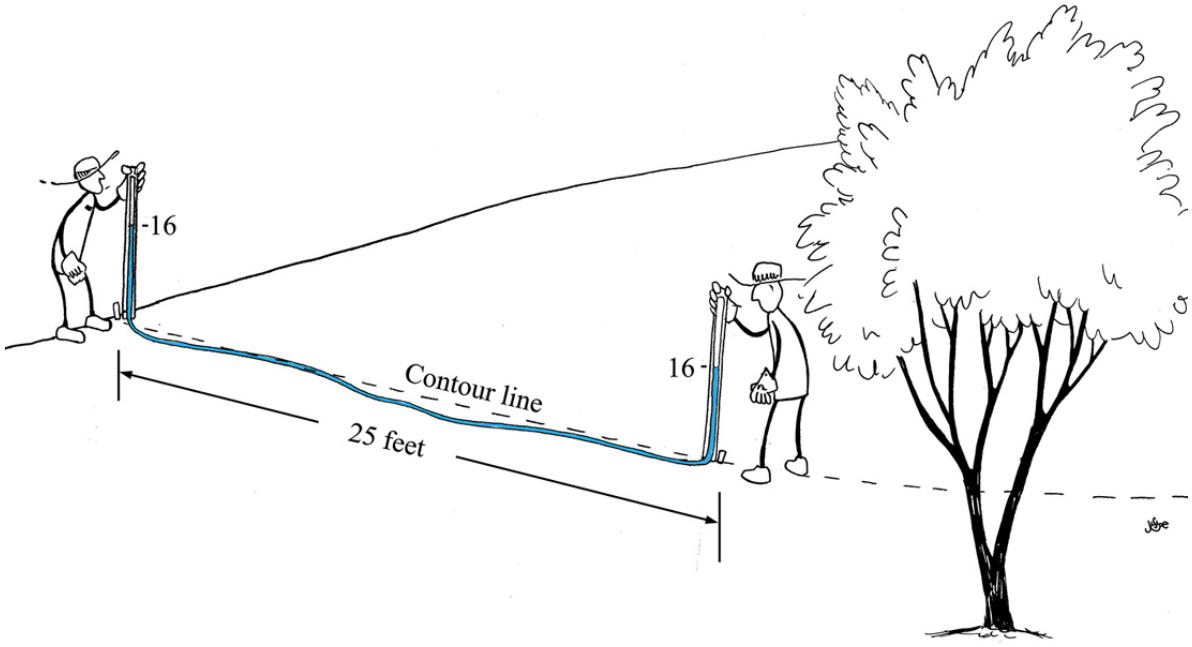


Fig. 9.6A. Marking a contour line, and placing distance markers along it every 25 feet

Once you have the contour line marked out to the distance you want, you are then ready to mark off the gradually sloping path you want the diversion swale to take across the natural decline (see fig. 9.6B). A bun-yip water level is my tool of choice to mark the path of the swale. The drop in the swale's slope can range from as little as 1:6,000 (0.016%) in fine sands (0.2-inch drop in elevation for every 100 linear feet of the swale)[3] to as much as 1:300 (0.33%) in more stable soils (a 4-inch drop in elevation for every 100 linear feet of swale).[4] The steeper the slope of the diversion swale the more quickly water will flow downhill, the less infiltration will occur along the path of the water, and the more the potential increases for erosion to occur along the water's path. The more gradual the slope, the more water can infiltrate, and the less likely erosion will occur. (See box 9.1 and the Spreader Drain story in the Real-Life Examples section of this chapter for more details on determining your swale's slope and marking your swale's route.)

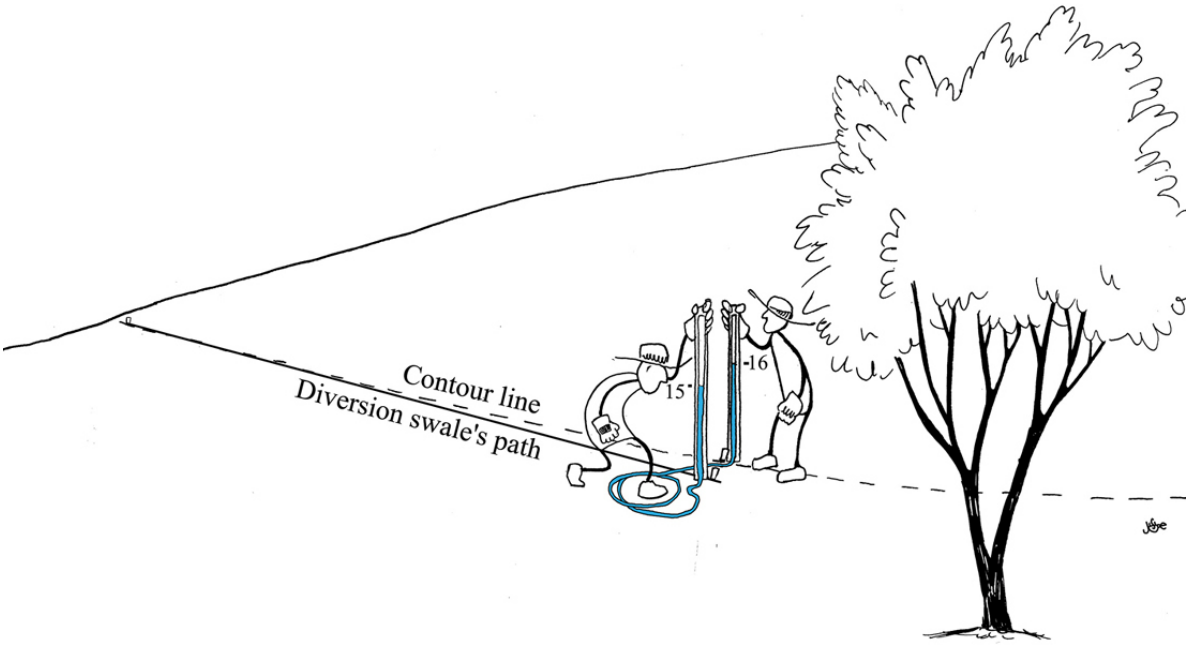


Fig. 9.6B. Using a water level to mark a progressive 1-inch drop off the contour line at every 25-foot interval to lay the swale's path at a 1:300 slope off-contour

Box 9.1. Marking the Route of a Diversion Swale with a 1:300 Slope: An Example

Step 1. Mark off a contour line in the area you want your swale to be placed (see fig. 9.6A, marking contour line). Then, figure out how much you want your swale to slope. This can range from 1:6,000 (gradual) to 1:300 (steep). In this case, a 1:300 slope is permissible because of very stable soil. The desired swale slope will determine the next step.

Step 2. Place distance markers (flags or stakes) along your contour line at even lengths—based on your slope ratio—from which you will mark the sloping path of the swale (step 3). For example, this swale will slope 1:300—that equals a drop of 1 inch for every 300 linear inches, or 1 foot for every 300 linear feet. So, you could place distance markers at 300-inch intervals along your contour line. But, most likely you'll find it easier to deal in feet with longer lengths, so divide the 300 inches side of the slope ratio by 12 (12 inches in a foot) to get the slope ratio of a drop of 1 inch for every 25 linear feet. That done, place distance markers every 25 feet along your contour line, instead of every 300 feet (fig. 9.6A). (If you wanted a 1:600 slope, you'd divide 600 by 12, to get 50, so you'd place distance markers every 50 feet.)

Step 3. Mark your swale's sloping path. At the first 25-foot distance marker along the contour line, measure a drop of 1 inch (fig. 9.6B) below the contour line. Mark this elevation with a flag or stake. Make a line from the beginning of the contour line to your new marker (1 inch below the contour's 25-foot mark). Then go to the next 25-foot distance marker along the contour line and mark a drop of 2 *inches*—every 25 feet the swale's path progressively drops another inch off contour. Continue the line of the swale's path from the last marker to this latest one. And keep going as such until you get to the desired end of the swale.

If dealing in metric measurements a 1:300 slope would equal a drop of 1 centimeter every 300 centimeters, or a drop of 1 centimeter every 3 meters.

Termination of diversion swales, and ponds

Remember and practice the principle, *always plan an overflow route, and manage that overflow as a resource*. Thus each diversion swale (or any earthwork) should ideally terminate at a feature that maximizes the on-site infiltration and beneficial cycling of water, such as an infiltration basin, pond (boxes 9.2 and 9.3, fig 9.7), or a gradually sloped, well-vegetated section of the landscape that will maximize the beneficial spreading and sinking (infiltrating) of the water's flow across the landscape (see Connect and Spread strategies in this chapter's Variations section).

Box 9.2. Ponds

Ponds can be an effective water-harvesting strategy or a wasteful water-consuming strategy. If you use rainwater as the *sole* water source, then you have a "water-harvester." If you design a pond that uses piped-in well or municipal water as its water source, then you have a "water consumer." Always avoid water-consuming ponds and fountains. This is especially true in drylands! (A possible compromise, using harvested water only, would be fountains running on rainwater harvested within a cistern, and when the cistern water dries up the fountain stops running until rains once again fill the fountain cistern. The cistern water, however, would likely be more efficiently used to irrigate a canopy of cooling, food-producing, and wildlife-attracting shade trees).

The decision to use water-harvesting ponds should be considered with caution and care. In the dryland environment, high evaporation rates can rob large amounts of water stored above rather than within the soil or closed cisterns.

The higher the rainfall and the lower the evaporation rate, the more sense it makes to use a pond. In the cool climate of northern California where 60 inches (1,524 mm) of rain can

fall in a winter, followed by a bone dry spring, summer, and fall, ponds can hold very large volumes of winter runoff for a fraction of the cost of a cistern of similar volume. Placed high in the landscape, gravity can distribute pond water around a site for irrigation, fire control, and domestic water supply.

Is a pond appropriate for your site? Perhaps so, if you have sufficient rainwater runoff to fill and maintain it through dry seasons and droughts, or else you are fine with letting it run dry during the dry seasons. A pond is probably not appropriate if you plan to supplement your pond with piped-in well or municipal water. For information on assessing pond location and building one, contact your local Natural Resources Conservation Service (NRCS) agent (found under U.S. Department of Agriculture).

Box 9.3. Tips on Pond Construction

- Make your pond deep rather than wide and shallow to reduce the surface area exposed to heat and evaporation. However, ensure pond slopes are gradual enough for animals to clim out should they accidentally fall in.
- Plant deep-tap-rooted, low-water-use shade trees or tall shrubs around your pond to defle the sun's heat and moisture-robbing winds. In southwestern Arizona, avoid thirsty cottonwoods and instead plant hardier native velvet mesquites.
- Stock your pond with *native* mosquito-eating fish to help prevent your pond from becomi a major breeding ground for mosquitoes. If these native fish get loose, they boost native fi populations rather than hurt them as exotic fish often do. Contact your local Game and Fis agent for help.
- Set your pond high enough in the landscape so you can distribute water by gravity.
- As with any water-harvesting strategy, your pond must have an adequately sized and stabilized overflow route.

See this chapter's Variations section, and appendix 4 for more pond resources.

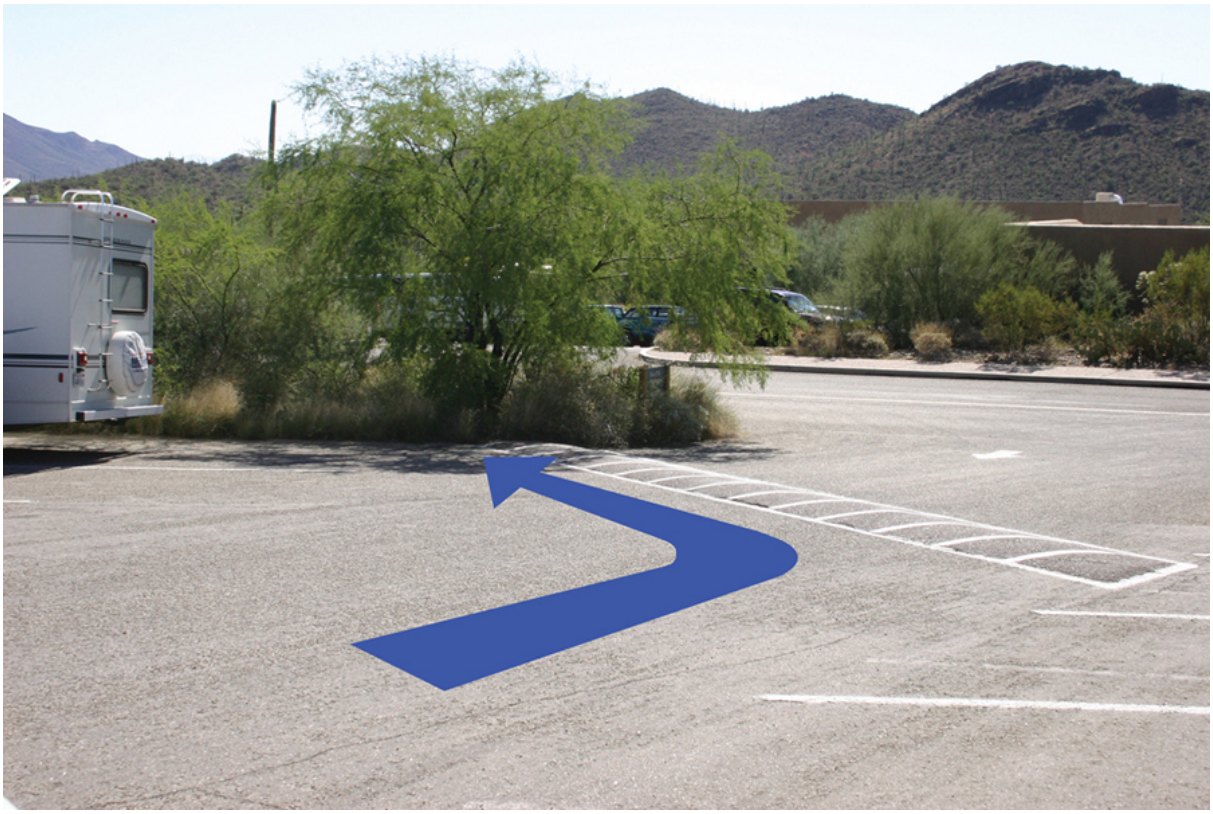


Fig. 9.7. A diversion berm/speed hump directing parking lot runoff into a vegetated basin. Arrow denotes water flow. Arizona-Sonora Desert Museum, Tucson, Arizona

A diversion swale can also redirect runoff to cisterns (especially when the catchment is relatively sediment free, and silt traps divert sediment before it gets to the cistern)—see figs. 9.8 A, B, C. But again, strategize how to make the most of that cistern's overflow.

Fig. 9.8A. A stabilized diversion swale built to collect hillside runoff and redirect it to a cistern in the Jaipur Fort built in 1726, Jaipur, India. This diversion swale and the cistern are still in use. The Maharaja opened the fort to the public in 1983, and it is now a tourist attraction.

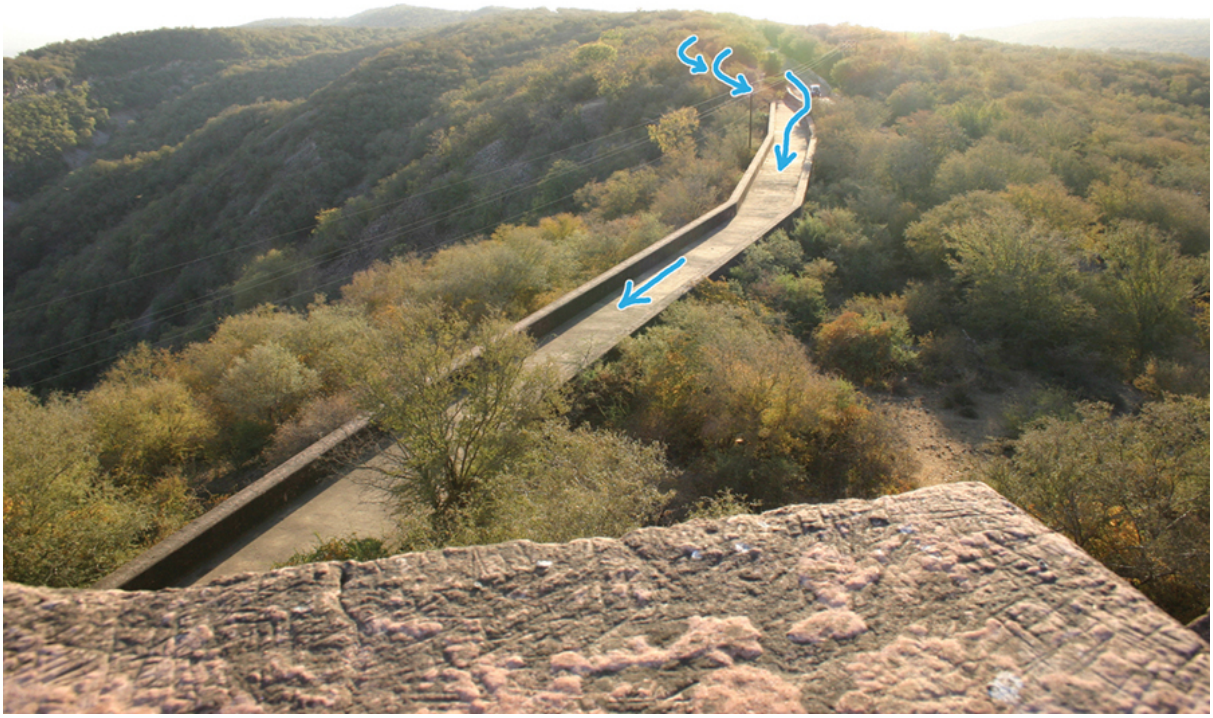


Fig. 9.8B. Diversion swale entering the Jaipur Fort (foreground), and the 2.4-mile (4-km) catchment in the background

Fig. 9.8C. Diversion swale (channel entering from lower left corner) directs water to enter a covered cistern in Jaipur Fort, India. Uncovered cells or square tanks (see people sitting at edge of the tank) capture the silt in the runoff, and the slope of the diversion swale itself is greatly reduced so silts settle out and relatively silt-free water enters the massive cistern (beneath square plaza-like cover with raised octagon in its center).

If using a diversion swale to move excess water from one water-harvesting earthwork to another, begin marking the diversion swale's location at the overflow spillway of the highest earthwork, then mark the swale's route at the appropriate slope to the planned inflow point for your next earthwork. If you find the slope of the diversion swale is too steep or too gradual, you may need to move the lower earthwork or its inflow point higher or lower to correct or adjust the slope.

Mark the diversion swale's route with stakes, flagging, surveyor's spray paint, or a line scratched deeply into soil. Do the same for the outline of any other water-harvesting earthworks with which the swale interconnects.

SPACING

As you would with a berm 'n basin, space your diversion swales according to their size and the expected volume of runoff. The smaller (meaning lower water-

holding capacity) the swale, and the higher the expected runoff, the closer together swales or other water-harvesting earthworks should be, which results in a smaller "microwatershed" serving each swale. The larger the swale and the lower the expected runoff, the farther the distance between swales should be, which gives each swale a larger microwatershed. See appendix 2, runoff calculations: Equations 1–3 are for calculating surfaces; equation 5 gives net runoff examples using an outdoor area with the surface's runoff coefficient.

APPROPRIATE SIZE

Diversion swales can range from a small furrow leading roof-downspout water to a vegetated infiltration basin, to a huge swale cut across acres of sloping land. Design your earthworks to handle the peak flow of runoff from large storm events (see Volume 1, chapter 2 on assessing your site, and the example of a 3-inch rainfall event for equation 5 in calculations appendix 2).

The diversion swale does not need to be sized like a holding basin because it moves rather than holds water. But it does need to be large enough to handle the peak flow of the incoming water. For example, if it is taking water from a culvert or downspout, the rule of thumb is to build the swale bottom width equal to 2 to 4 times the diameter of the culvert or downspout with a depth equal to the diameter—this applies to the recommended swale slopes ranging from 0.17 to 0.33%. The more vegetation within the swale the wider the swale, since the plants will slow the water's flow. That way the channel of the diversion swale does not adversely constrict the flow of water coming into it. For example, in determining the depth and width of a diversion swale to direct overflow water from one backyard-scale water-harvesting earthwork to another, make all the diversion swales the same ample size so the inflow and outflow capacity for each swale will be equally large and will be able to transport all water safely. I don't use any exact calculation, but instead work on the intuitive level, making sure my diversion swale width exceeds the diameter or width of the incoming channel; however, equation 17 in calculation appendix 2 provides further information on sizing your diversion swale. If using a series of diversion swales to collect runoff from a large catchment area plus direct overflow water from one large-scale water-harvesting earthwork to another (such as from one earth dam to another), you may need to increase the size of the swale as you move down the watershed, since the swale will be collecting both overflow water and a significant amount of runoff from the land above the swale.

Err on the side of making the berms and basins of your diversion swales bigger to reduce the chance of a berm eroding too quickly or blowing out in a big storm. As a rule of thumb, make the base of the berm around 4 times as wide as the height of the swale. See fig. 9.9. In gopher country (regardless of soil type), go wider with your berms so the critters' holes will be less likely to blow them out. Make your berms wide enough to double as accessways wherever the potential exists.

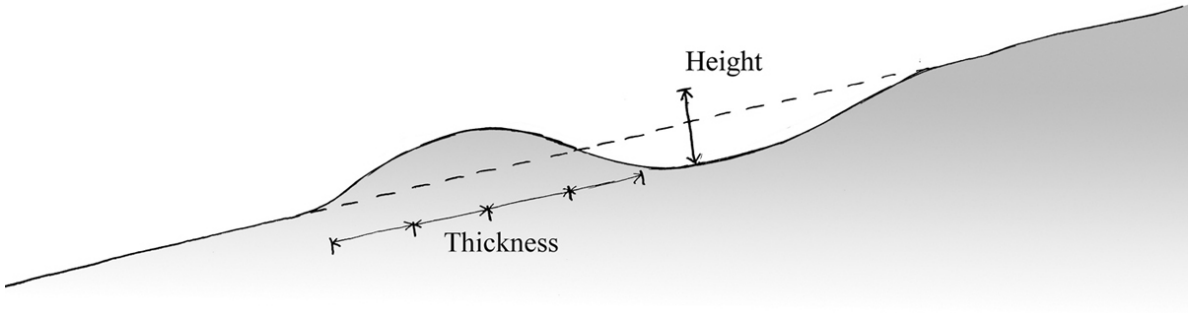


Fig. 9.9. Berm base 4 times as wide as berm height

CONSTRUCTION

To construct a diversion swale, dig a basin just upslope of the markings you made delineating the planned route of your swale, then use the excavated dirt to build your dirt berm downslope. When creating the berm, go ahead and pile the dirt around existing plants along your marked line. Smaller plants may get completely covered, but larger, only partially covered plants should recover.

Give the sides of the berms and basins of your swales a gradual slope for more erosion resistance and to make revegetation easier. A 2:1 slope works, but a more gradual 3:1 slope is more stable.

To firm up your berms, compact them by walking on them and tamping them down evenly along their length with your feet. Berms built by graders and backhoes can likewise be compacted by the machine.

Do not compact the basin where you want water to infiltrate along its course.

LOCATION AND CONSTRUCTION OF APPROPRIATE SPILLWAYS FOR OVERFLOW

The "overflow spillway" of a diversion swale is the lower end of that swale. To control and utilize overflow water, the swale should ideally terminate at a point in the landscape where land slope is gradual to level, vegetation is well established, and soil has not been disturbed—so surplus water can be discharged as calm,

spread out sheet flow. Surplus water can also be discharged to a water-harvesting earthwork, a stable natural waterway, or a storm drain.

If the final destination of the water is an earthwork such as an infiltration basin, the lower end of the diversion swale should have a gradual slope right up to the point that it meets the level bottom of this final basin. Water pooling in the basin will diffuse the force of the incoming water from the diversion swale, which will temporarily back up along the lowest section of the swale. That basin can then overflow as calm, spread out, shallow sheet flow if the basin's downslope bank is wide, level and vegetated—similar in form to a *sheet flow spreader* described in chapter 10 (fig. 9.10). See fig. 9.11 and Spreader Drains in this chapter's Variations section for another sheetflow overflow option.

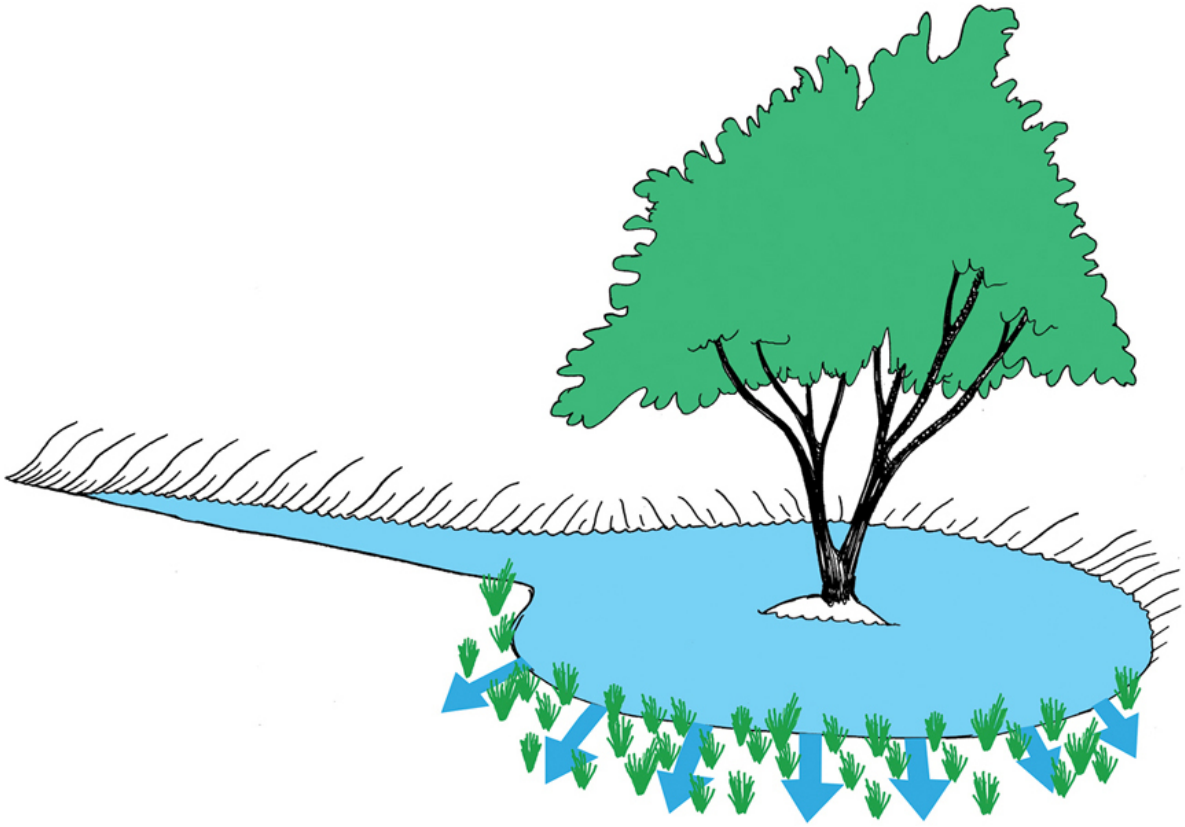


Fig. 9.10. Water pooling in basin at the base of diversion swale then overflowing as calm sheet flow. Compare to sheet flow spreader strategy in chapter 10.

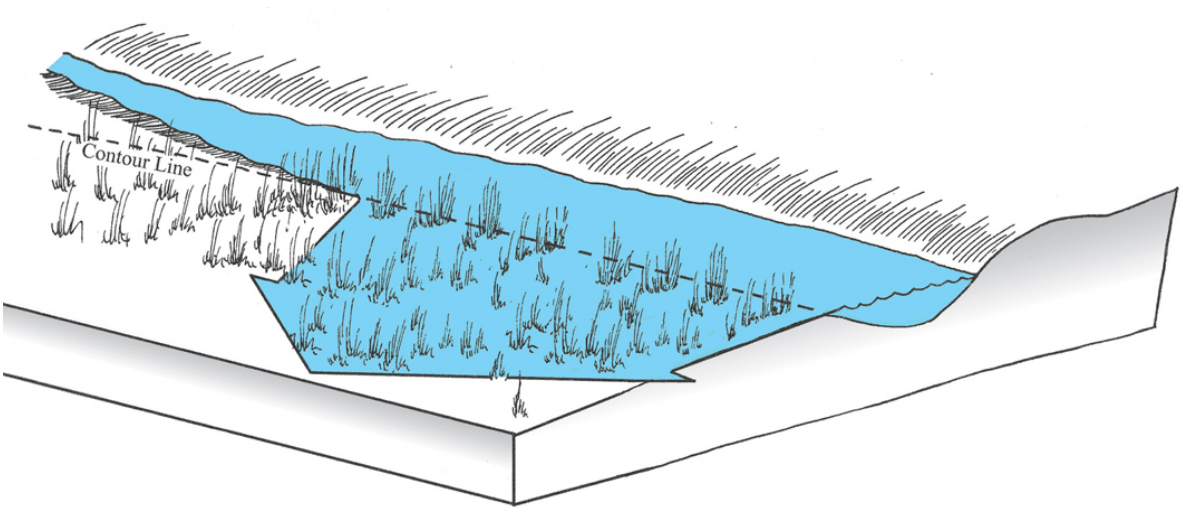


Fig. 9.11. The bottom length of the spreader drain is level so backed-up water overflows as a thin sheet of water. Water pools in bottom level section of basin first. Once full, the pooled water overflows evenly as sheet flow over the level downstream edge of the drain.

This type of gradual, spread-out overflow is less prone to erosion and failure than steeper (over berm) and narrower, more channelized overflows like those in figs. 3.14B and 3.17.

Any sudden drop in grade where the lower portion of a swale meets an earthwork must be stabilized. A combination of stone rip-rap with vegetation usually works well (see chapter 10 for examples).

PLANTING YOUR DIVERSION SWALE

Planting strategies depend on the intended use of your swale. If it's primarily to divert water, planting in the basin would impede the flow of water, so instead plant the berm, the area just downslope of the berm, and the spillway. If the goal is to infiltrate water along the length of the diversion swale, and divert only excess water, then you may be able to seed the basin with low-growing vegetation like native grass that will increase infiltration rates along the length of the swale. But, the banks of your swale must be high enough to ensure that water slowed by, and backing up behind, the vegetation will not erosively blow out the swale's banks.

MAINTENANCE

Check on your diversion swales periodically, especially during or just after big rains. Make any needed repairs or adjustments. Berms may need to be built higher or wider, or blockages in the channel may need to be cleared. If an excessive

amount of runoff is entering or eroding the swale, create more water-harvesting earthworks upslope of the swale within its watershed. Check the condition of the bottom of the basin to see if there is evidence that soil is being carried away along with the water flowing through it. This may indicate the slope of the diversion swale is too steep. Water flow can be slowed down by constructing small one-rock dams or ORDs (see chapter 10) periodically within the confines of the swale channel. Be sure the ORDs do not rise above the banks of the swale and inadvertently divert water out of it. You can plant trees on the downslope side of the dams to utilize the harvested water (fig. 9.12).

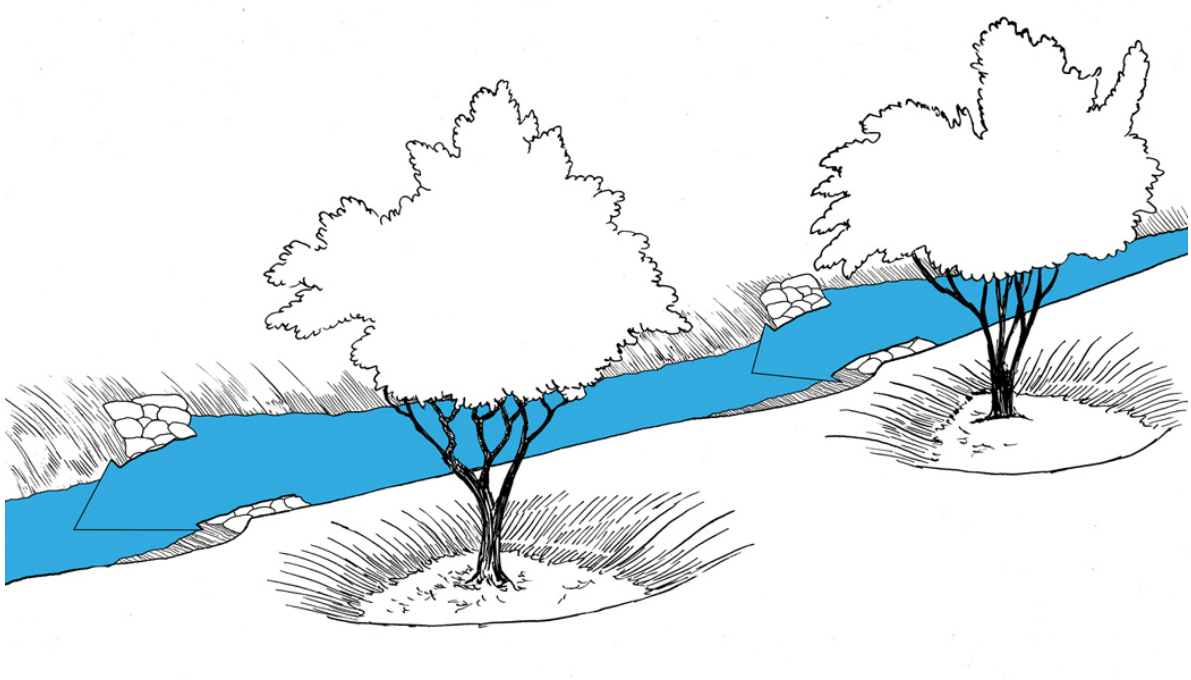


Fig. 9.12. Low one-rock dams slowing the flow within a diversion swale

VARIATIONS OF A DIVERSION SWALE

SPREADER DRAINS

Spreader drains are designed with the upper and middle portion of their basin to slope gradually like a typical diversion swale, but the bottom length is constructed dead level on contour without a downslope berm to create a very wide and level overflow spillway. Water flowing down the swale slows to a crawl along the level bottom section, then stops at the end of the drain's basin. Water slowly collects, backs up, and rises within the bottom end of the swale's basin until the water crests and evenly overflows the level downslope edge as a shallow spread-out sheet

flow, rather than a deep constricted flow. The overflow area must have a *gradual* slope and be well stabilized with vegetation to prevent erosion and increase water infiltration. However, in degraded land, or devegetated areas, compaction or even concrete stabilization of the spillway might be appropriate, while simultaneous efforts speed the revegetation of the area just downslope of the stabilized spillway (fig. 9.11).

Spreader drains slow and diffuse the force of incoming water, encourage its infiltration along their gradually sloping furrow, and finally spill and spread any overflow water as slow, wide sheet flow. They help prevent erosion and gully formation by diverting, diffusing, and infiltrating the channelized water from roadside drainage ditches or small earthen dams. In wetter areas spreader drains can be used to irrigate fields or pastures with sheet flow. Spreader drains should be sized to handle peak storm flows from their catchment.

Spreader drains can be constructed with a berm on the up- or downslope side of the sloping sections of their basin. Although there is no berm on the down-slope side of the level end section of the basin, there can be one on the upslope side. This ensures a more gradual overflow spillway along the swale's downslope edge than would be the case with a mounded berm. Sometimes the excavated dirt is placed in mounds on the upslope side of the basin to allow some additional infiltration of runoff from upslope areas into the drain,[5] though as you will see in the spreader-drain case study in the Real-Life Examples section, the excavated dirt can create a nice raised road or path in the form of a continuous berm upslope of the basin. Either way, additional water-harvesting earthworks, such as berm 'n basins, may be needed upslope of the drain to prevent excessive overtopping of the drain's upslope bank or berm and keep fast-moving or sediment-rich runoff from entering the spreader drain and causing erosion.

ROLLING DIP DIRT ROAD DRAINS

Dirt roads tend to be the biggest maintenance burdens in rural areas due to poor road placement, construction, and/or upkeep. These factors can result in water being retained on dirt roads, causing soil erosion, formation of mud bogs, dehydration of the land on the downslope side of the road, and other problems. *Rolling dips* are one strategy to remedy this. Unlike roadside drains alone, which can be bypassed by water that flows in wheel ruts (fig. 9.13), a rolling dip is a wide cross-drain system with a *dip drain* in the road, a wide *lead-out ditch* to the side of

the road, and a wide *roll-out berm* on the road that forces the water into the drain and ditch (fig. 9.14).

Fig. 9.13. Blading of dirt road during its construction and maintenance has resulted in the road becoming the lowest point in—and thus the drain of—the landscape. Water takes the path of least resistance, thus much of the water erosively flows down the wheel ruts in the road, bypassing the road drain. Altar Valley, Arizona

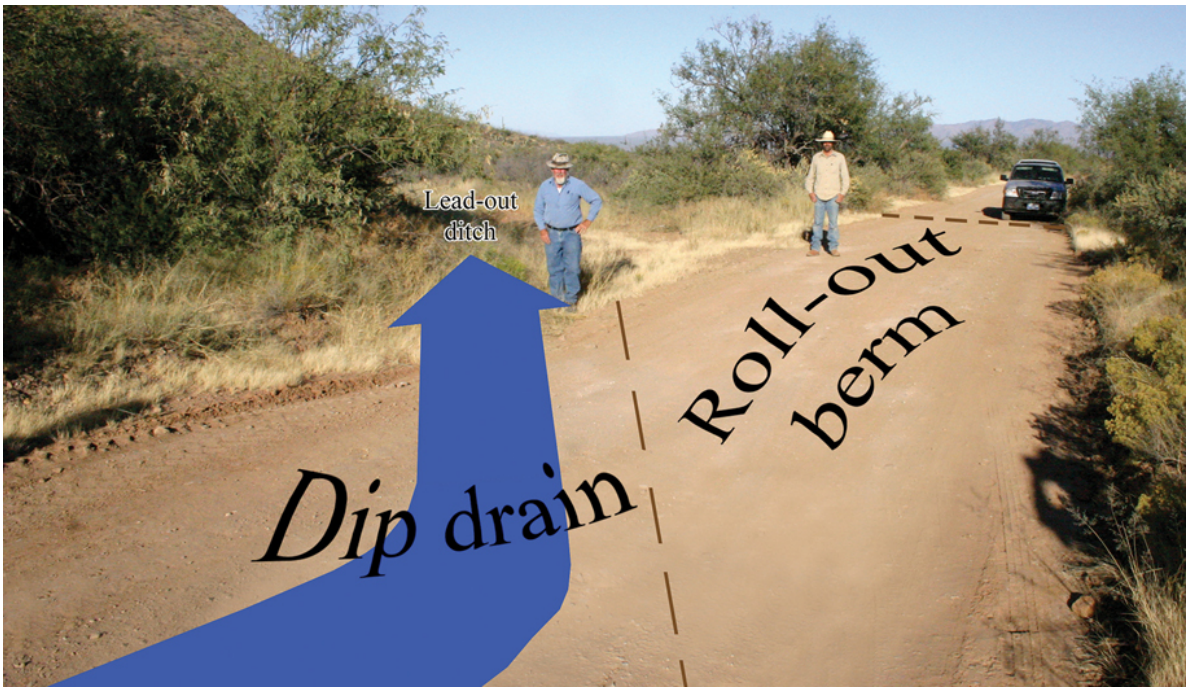


Fig. 9.14. Blue water flow arrow denotes flow diverted off a road in a rolling dip. Dashed line denotes the boundaries of the roll-out berm, which prevents water from continuing to flow down the road. Bill Zeedyk (with white beard) stands where the water flows from the dip drain into the lead-out ditch. Elkhorn Ranch, Altar Valley, Arizona

Note: in the rolling dip context, lead-out *sponge* may be a better term than lead-out *ditch* since its purpose is to maximize the spread and infiltration of water in the landscape (not the road). This is why it is ideally wide and shallow, not narrow and deep, and is directed to vegetation—not a gully.

The dirt excavated to construct the rolling dip strategy's dip drain and lead-out ditch can provide some or all of the dirt needed to build the roll-out berm. However, dirt may need to be hauled in if there's not enough dirt to complete the roll-out berm, if the local dirt is not suitable for a road surface, if this would be less expensive, or to minimize disturbance off the road. If you are using a bulldozer or tractor with a blade, dig the lead-out ditch the width of the blade. Make sure the bottom of the ditch is flat, with no incision that could channelize water. Typically, native grass seed is broadcast within the imprints of the bulldozer tracks or tractor tires in the lead-out ditch (fig. 9.15).

Fig. 9.15. Bulldozer track imprints filled with water just after a rain within a lead-out ditch. These imprints are ideal for increasing germination of broadcast seed. See chapter 6 - Imprinting for more

Base the length of the rolling dip's roll-out berm, and its dip drain, on the size of the typical vehicle that will drive over it—for example, a 20ft (6m)-long pickup

truck. The vehicle's length should be able to fit atop the roll-out berm, and the vehicle should also fit within the dip drain. If the typical vehicle will be a truck and its trailer, everything would need to be elongated (fig. 9.16). By sizing components to fit typical vehicle lengths, the rolling dip and its roll-out berm will be at a stable, gradual grade and not create a road-hazard bump. Built this way, one can safely drive at 50 miles per hour (80 km/hour) over a rolling dip. Roll-out berms can be shorter in length and less gradual when located on low-speed roads or where you want them to act as speed-reducing speed humps.

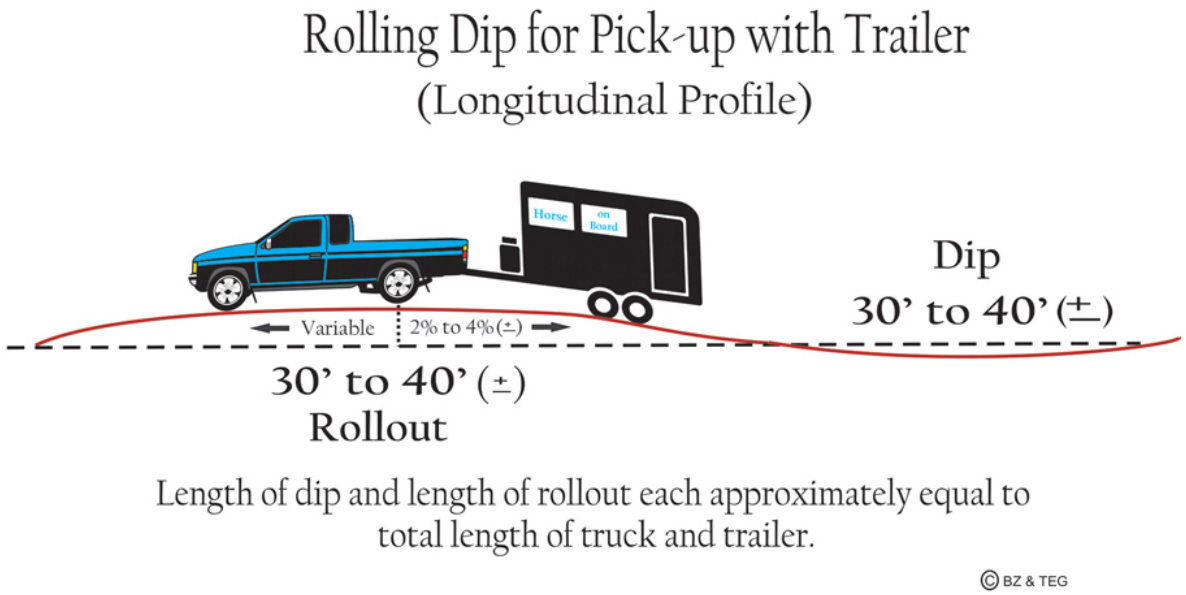


Fig. 9.16. A rolling dip must be sized according to the dimensions and clearance of the type of vehicle that has the most demanding requirements. Reproduced with permission from *Water Harvesting from Low-Standard Rural Roads* by Bill Zeedyk.

The first step in building a rolling dip strategy is to find a spot where you can beneficially drain the road. This spot must be lower than the road, and should ideally have a gradual slope that will calmly spread the water out as sheet flow to benefit vegetation, rather than having a steep slope that would erosively channelize the flow.

The next step is to mark out three components: 1) the *dip drain*—the drain that precedes the roll-out berm, 2) the diagonal leading edge of the roll-out berm that you will construct across the road, and 3) the *lead-out ditch*—the off-road drain into which you will direct the road runoff (fig. 9.17).

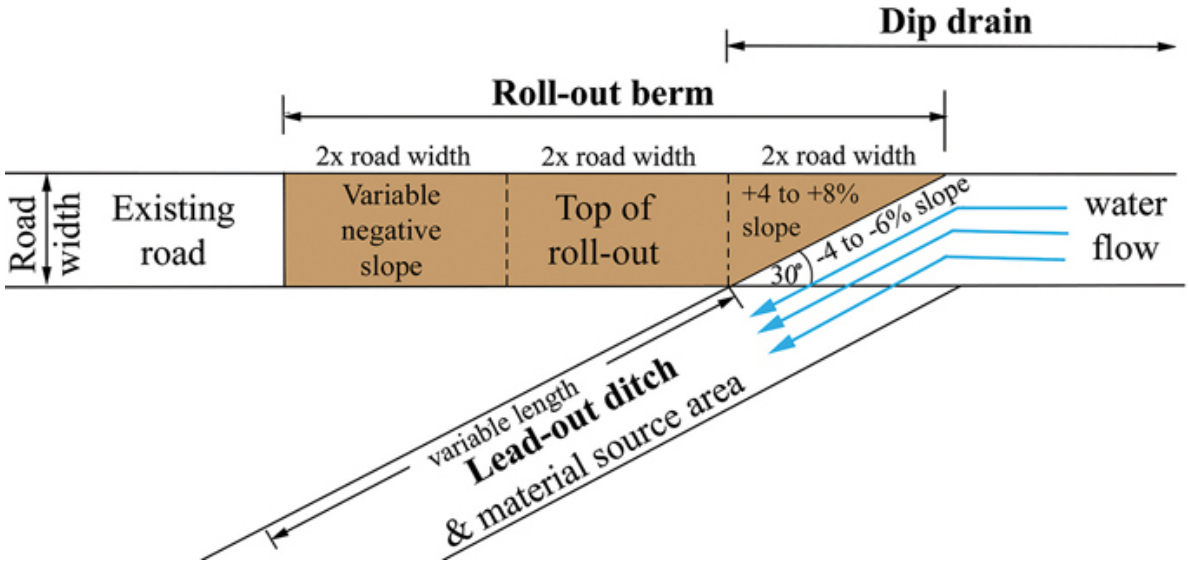


Fig. 9.17. Rolling dip, plan view. The material removed (cut) from the dip drain and lead-out ditch areas is moved up on the roadway and becomes the fill for the elevated roll-out berm. The length of the top of the roll-out berm varies depending on the length of vehicle you are designing for, but is usually not less than two times the width of road for a single lane road. Adapted from *Water Harvesting from Low-Standard Rural Roads* by Bill Zeedyk

The line where the dip drain meets the roll-out berm should be at a 30˚ angle to the length of the road (fig. 9.17).[6] To achieve this, measure the width of the road at the lead-out ditch location. Standing on the opposite side of the road from the lead-out ditch location, walk upslope along the road a distance that is two times the width of the road, then stop. You will then be standing at the starting point of the line where the dip drain should meet the roll-off berm in order to lead water straight into the lead-off ditch (fig. 9.17).

When done, the dip drain should have a 4 to 8% downward slope toward the lead out ditch—steep enough to flush away accumulating sediments.[7] The lead-out ditch should have a downward slope of at least that steepness or steeper, otherwise the road runoff will slow down and drop sediment in the ditch, clogging it and leaving a puddle in the dip drain on the road (see the Erosion Triangle in Tracking of Water and Sediment Flow section of chapter 1). Keep in mind that the vegetation that will grow in the lead-out ditch will also slow runoff flow. Road grades flatter than 2% are too flat to drain efficiently, so if you have this limitation, consider narrowing the channel of the roll-out ditch to increase the depth of flow and the flow's ability to carry sediment away.

As to how often to place drains along a dirt road or path, Bill Zeedyk recommends you drain the road:

- **Your first chance(s)**

Start just below the top of the road's watershed to reduce the amount of water erosively flowing down the road; and the first chance you get just after the road gets out of a canyon-like section where the road is lower than the landscape to either side.

- **Your best chance(s)**

Ideally, drain the road where it can do maximum good and the least harm. Drain to the spots where the water will spread (fig. 9.18), not gully. Gradual well-vegetated slopes are best as opposed to erosive, bare, steep slopes. Avoid draining a road into buildings or other dirt roads.

Fig. 9.18. Van Clothier shows how native grasses have grown waist high where they receive road runoff inputs from a rolling dip's lead-out ditch placed in a best chance location. Elkhorn Ranch, Altar Valley, Arizona. See AltarValleyConservation.org for more on their water-harvesting projects.

- **Your last chance(s)**

Drain the road just before incised canyon-like sections where the road is lower than the landscape on both sides and there is **no chance** to drain the road.

As Bill Zeedyk reports of his work in Altar Valley, Arizona, "On dirt roads where regular traffic included tractor trailer trucks on daily basis, we made the bottom of the dip 60 feet (18 m) long, the top of the rollout 60 feet (18 m) long, and the backslope ramp 60 feet (18 m) long making for smoother ride at high speed. We had to haul in sufficient material to build the rollouts. Rough calculations of fill needed were 6 yards (5.5 m) wide by 20 yards (18.2 m) long by 1/3 yard (1/3 meter) high, equaling 40 cubic yards (30.5 m^3). Fill needed for downslope ramp was equal to amount excavated from the dip, dip drain and approach. We used about 3-5 rolling dips per mile (or one every 1,000 feet or so) spacing where needed. Hauling in the fill was expensive, but it greatly reduced the cost of grading the road and cleaning ditches after every rainstorm so the County was glad to do it and began using this type of treatment on other roads especially school bus routes and mail routes since it was cheaper than having to blade the road after each storm. Key decision—what sized vehicle will need to use the road on regular basis? Pickup? Pickup with horse-trailer? Eighteen wheeler? Then size the rolling dips accordingly."[8]

See *A Good Road Lies Easy on the Land: Water Harvesting from Low-Standard Rural Roads* by Bill Zeedyk (available on-line for free download) for much more comprehensive information and strategies.

And see chapter 10 for strategies used to stabilize steeper (and potentially more erosive) lead-out ditches that drain rolling dips.

CONNECT AND SPREAD

Connect and spread strategies reconnect and restore productive, dispersed, spread out flow (sheet flow) to surfaces that have been erosively channelized and gullied.[9]

Two such strategies—the ***plug and spread*** strategy and the ***plug and pond*** strategy—are used to reconnect flows in gullied channels to their adjacent wide, vegetated floodplains. The goal is to spread water onto wide, relatively flat landforms that were, or still are, wetlands, as identified by the presence of hydric soils with dark, fine-grained aggregate. This is accomplished by carefully diverting water out of gullied channels to locations where the water can flow onto, and infiltrate into, a much greater surface that has stabilizing vegetation. (See the

patterns and principles section at the beginning of chapter 10 for more on how to collaborate with the natural relationships between channels and their floodplains).

The *plug and spread* strategy is used for channels with ephemeral water flow (water that flows only hours or days—and not more than 30 days—following rainfall) and/or intermittent flow (water that flows more than 30 days, but less than a year).

The *plug and pond* strategy is used for channels with perennial (year-round) flow and in perennial wetlands.[10] It was developed by hydrologist Dave Rosgen.

According to practitioner Bill Zeedyk, who applies these strategies in northern New Mexico and beyond, "Depending on the situation, both strategies can increase forage yields for livestock, improve habitat for wildlife, increase groundwater storage, attenuate floods and dissipate flood energy. Reconnected wet meadow soils can produce up to twenty-five times more forage than adjacent upland soils, 3000-5000 pounds (1200-2000 kg) per acre (0.4 ha) per year as compared with 100-200 pounds (40-80 kg) per acre (0.4 ha) from nearby uplands."[11] Additionally, they help sequester carbon in the living soils and the vegetation they support.[12]

As shown in fig 9.19, a *plug and spread* strategy is always combined with placement of a well-compacted berm placed atop the crest of the plug. The plug is intended to stop water from flowing down the eroded channel. The berm is to stop flood flows from flowing over the plug. The plug and the berm are constructed using soil taken from a wide, shallow depression or bay to the side of the channel—do *not* deepen the channel and risk headcut erosion. Water filling the *bay* overflows to the side of the structure at a level, on-contour spillway called the *brim*. This at-grade spillway must be well vegetated with existing stabilizing vegetation (figs. 9.19 and 9.20). From there, water flows to a stable, gradually sloping area that is as wide as the topography will allow. The goal is not to maximize water storage upstream of the plug and its associated berm but instead to maximize the spread of flood flows across the valley's vegetated floor, so your goal is to *minimize storage and maximize spread*.

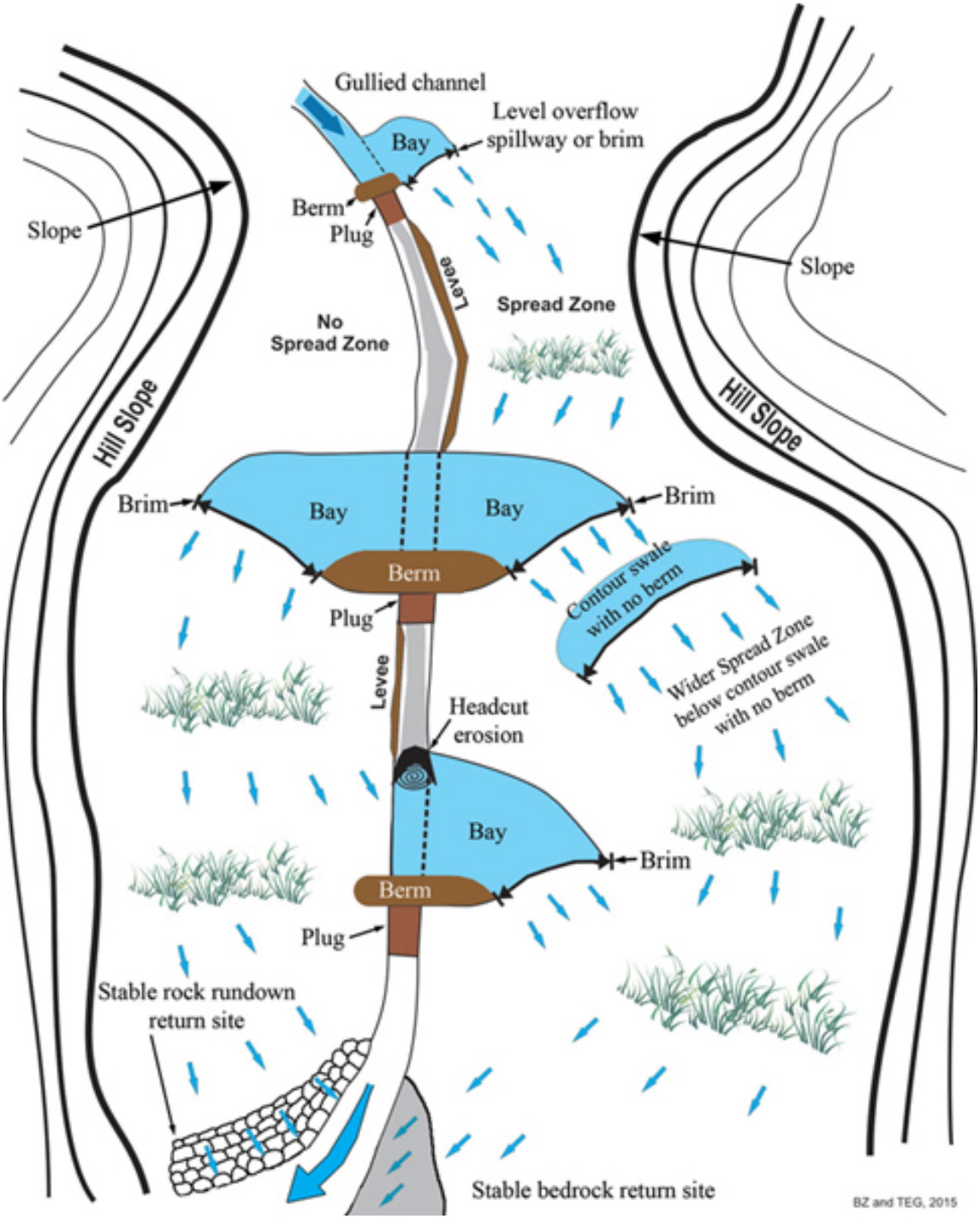


Fig. 9.19. A typical plug and spread complex. Reproduced and adapted with permission from *The Plug and Spread Treatment: Achieving Flood Control, Soil Health and Biological Diversity* by Bill Zeedyk.

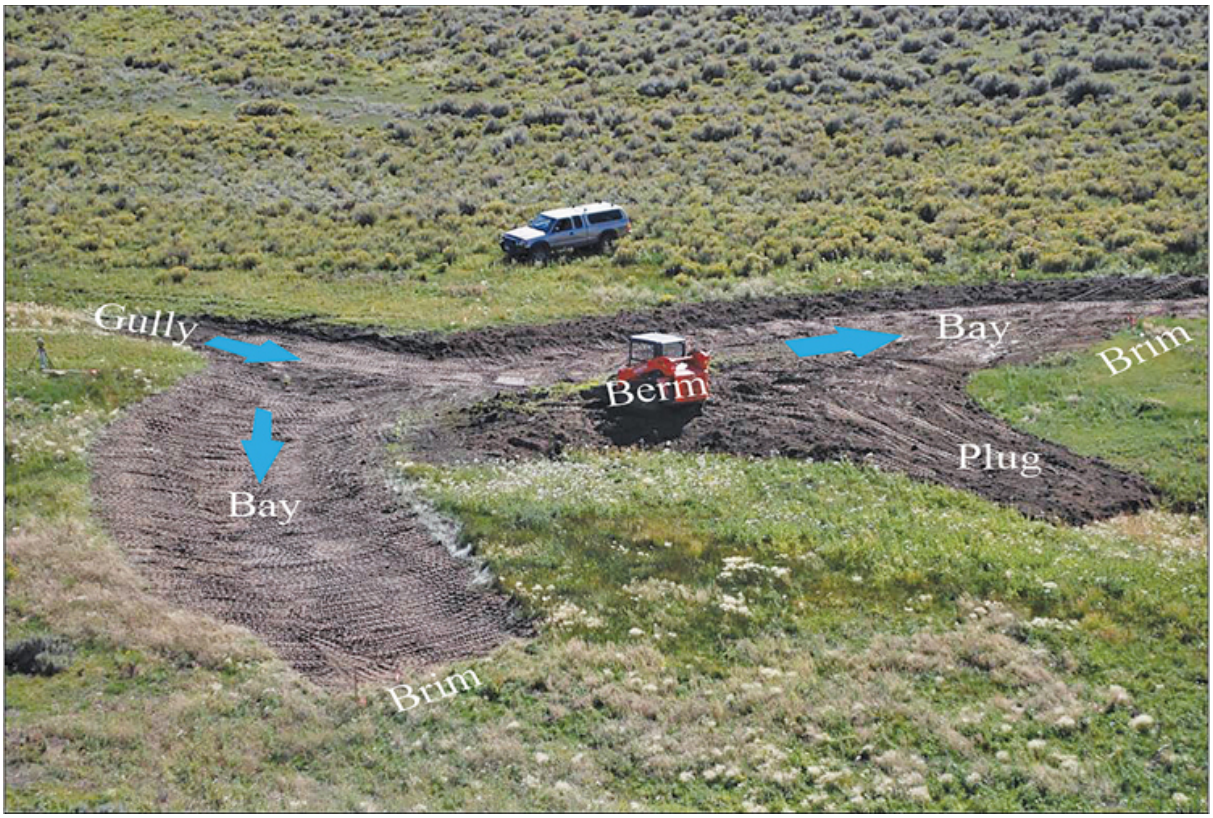


Fig. 9.20. Key features of a typical *plug and spread* structure. Photo: Betsy Neeley. Reproduced with permission from *The Plug and Spread Treatment*.

The *plug and spread strategy* lacks the stabilization of wetland vegetation, so it needs the berm atop the crest of the plug to reduce the chance that water overtops and washes away the plug during larger flood events. You may need to armor both the berm and the plug with rock to help withstand erosion, especially on the upstream ends of the berm where it abuts flowing water. Furthermore Steve Vrooman, of Keystone Restoration Ecology, notes that in areas experiencing grazing pressure from cattle or elk, the *plug and spread's* on-contour overflow brim(s) often gets trampled and channelized by the grazers. In this case, add level-topped one-rock dams or sheet flow spreaders (see chapter 10) at least 4 feet (1.2 m) wide along the entire downstream width of the brims, since grazers don't like stepping on the rock. Low spots in the brim can be made level with the rest of the brim by using larger rock to fill in those low spots. All rocks should be large enough that they don't move, and it's critical to check spillways after flood events and repair if needed.[13]

Where a healthy perennial wetland still exists, use a *plug and pond* strategy to divert water out of a gully and onto the adjoining floodplain/wetland. The goal is

to maximize the spread of flood flows into existing wetlands and to expand those wetlands using increasing water inputs. Water diversion is accomplished by constructing a well-compacted earthen plug in the channel then fully covering and stabilizing the plug using wetland sod. No berm is constructed in the plug and *pond* strategy.

To construct this strategy, start by removing existing wetland sod to a depth of at least 8 inches (20 cm) from the area where the *plug and pond* will be constructed. A skid loader is typically used to do this work. Stockpile the wetland sod. Get the soil needed to build the plug by taking it from the pond area that you are constructing upstream of the plug (similar to soil excavated from the bay of a *plug and spread*). Build the plug, then use the stockpiled wetland sod to cover the plug with a dense living mat of vegetation (sedges provide the greatest resistance to erosion). Shape the pond to direct overflow water from the pond area via a lead-out channel (similar to a *plug and spread's* bay) to a wide, level, on-contour spillway or brim that is constructed at-grade and is stabilized by existing dense wetland vegetation.[14] As with the *plug and spread* strategy, the on-contour overflow brims of *plug and ponds* may need level-topped one-rock dams or sheet flow spreaders to provide additional stabilization in areas experiencing trampling or grazing pressure from cattle or elk (see chapter 10.)

Both *plug and spread* and *plug and pond* structures must be built to manage large flows and high velocity flood events. To prevent water from eroding through *plugs* in these events, the structures should be built to divert and spread the water broadly across the spread zone.[15] Spillways should be sized to handle the full volume of high flood flows, so err on the side of wider, higher-capacity, level spillways.

Bill Zeedyk provides some additional considerations to keep in mind as you implement these strategies:[16]

• Is your valley sufficiently wide to justify the effort? To be economical in a pasture context, the width of the valley surface to be wetted should be at least six times the width of the gully to be plugged. However, the effort can still be worthwhile in a narrower floodplain from an environmental perspective.

• How can you create the most effective spread zone area for the least cost? Remember that the spread zone, not the structure, is the primary producer of the desired economic and environmental benefits—so place accordingly. Shifting the

structure's location just 10 - 20 feet (3 - 6 m) to increase spread can make a big difference.

• Is there a stable return site where water flow can safely reenter the channel? A stable return site is needed to prevent or control erosion that could occur when the flow from the spread zone eventually reenters the channel. You can use a natural return site if it is gradually sloped and well vegetated, or composed of bedrock (fig. 9.19). Or you can construct a return site using erosion control techniques such as a Zuni bowl or rock-mulch rundown (see chapter 10).

• Are suitable materials available on-site to construct a stable plug? Loam, clay, and clay loams are acceptable. Sand, gravel or sandy loams do not compact well enough, and are not acceptable.

• Is there evidence of hydric (wetland) soils or indicator plant species? The goal is to recreate hydrological conditions that were natural to the site prior to drainage/disturbance, not to irrigate an upland area that was never wet.

To successfully site, build, and maintain these structures, you must first read these comprehensive guides: *The Plug and Spread Treatment: Achieving Flood Control, Soil Health and Biological Diversity* by Bill Zeedyk and *The Plug and Pond Treatment: Restoring Sheetflow to High Elevation Slope Wetlands in New Mexico* by Bill Zeedyk and Steve Vrooman. Both are available online for free download.

Several additional concepts/strategies that can be helpful when undertaking this work in a broad valley in the wetland or former wetland context include:

• A ***contour swale with no berm*** can be constructed downgradient of a *plug and spread's* overflow rim to spread the sheet flow even more widely (fig. 9.19). Water fills this contour swale's basin, then spills over the level, full-length, on-contour spillway of undisturbed intact vegetation to further distribute the flow.

Berm-less contour swales can be used to create a series of cascading swales, directing water to one side or the other of a wide, relatively flat valley, and to divert water around headcuts as an alternative to headcut-stabilizing rock structures (presented in chapter 10). But this only works if you have a wide, flat, vegetated valley floor on one side or the other of the headcut.[17]

• A ***low levee berm*** can be constructed in instances where you want larger floods to flow both over a contour swale's spillway or a plug and spread's spillway, and

then to the side of the structure where existing topography will spread the flow even further, rather than flowing back to the gully. To do this, you can build a very low levee berm (just inches or centimeters high) to keep water from flowing where you don't want it, so it instead flows where you want it to spread (fig. 9.19 shows how low levee berms were used to keep water that was spread out by a *plug and spread* from flowing back into the gullied channel).

• A ***worm ditch*** is a bypass trench—typically hand dug—at least 2-feet (60-cm) wide and 1-foot (30-cm) deep, that directs water away from the headcut (and its eroding downstream gully channel) to an expanse of well-vegetated existing or former wetland located to the side of the channel (9.21A). The intake point of the worm ditch is dug upstream of the headcut (see chapter 10) where it will collect most of the concentrated runoff. The alignment of the ditch is then either lateral to the gully— partially spilling/overflowing along the full length of the ditch's downslope bank (and well away from the gully) to maximize spread (small one-rock dams can help with this), or is a meandering path that reduces the grade/steepness of water flow in the ditch to half the steepness of the gullied channel next to it. You can achieve this reduction in steepness by laying a rope along the section of the gully the ditch will parallel, then laying a length of rope that is *twice that long* to mark the minimum length of your more meandering, and thus more gradually sloping, ditch. The meandering ditch then overflows to another flow-spreading strategy such as a sheet flow spreader (see chapter 10).[18] See the free online download of *Characterization and Restoration of Slope Wetlands in New Mexico* by Bill Zeedyk for more information.

Follow up wisdom from Bill Zeedyk:

It is best to have a variety of context-specific treatments when regenerating an eroded site. And don't have an expectation that you'll get it all correct on the first go. Rather, expect to come back regularly, observe the effects of your work and the natural flows, and make needed changes accordingly (this is the water-harvesting principle *continually reassess your system: the "feedback loop"*). This work requires long-term commitment, which will reward you and the land with evolving understanding and effective systems—not short-term commitment that lacks follow up, evolution, and effectiveness.

For example, in fig. 9.21A, a small diversion structure was built within the gully at site 21. However, the gully banks where higher than the diversion structure so the diversion structure did not direct water back out on the floodplain. Bill

thought the worm ditch (site 20) above would be sufficient to induce all the water flow that was needed. However, with follow up observation, he realized the worm ditch could not sufficiently spread the water because the unwetted area was slightly raised, forcing water flow around it rather than across it. Installing the plug and pond at site 21 shown in fig. 9.21B remedied this.

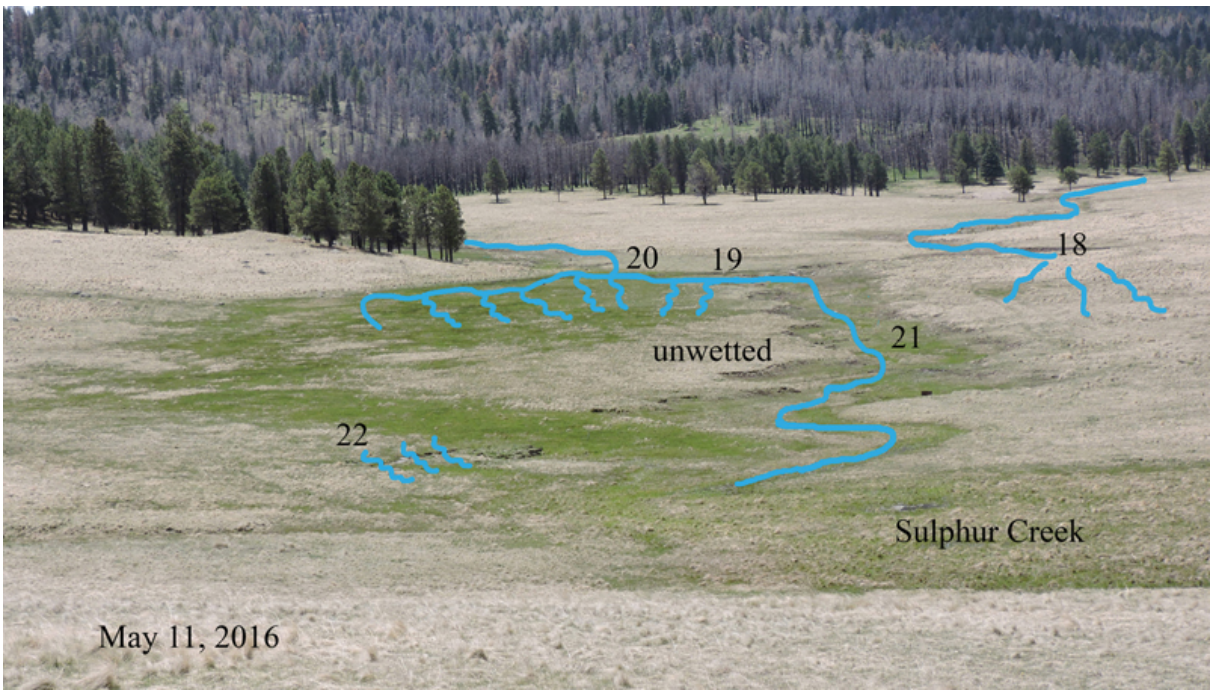


Fig. 9.21A. Sites 19 and 22 *plug and ponds*. Site 18 *plug and spread*, and Site 20 *worm ditch*. Treatments constructed in 2015. This pattern of varied treatments was used to disperse surface flows more widely. The structure initially installed at Site 21 was not effective, leaving the central area unwetted. Credit: Bill Zeedyk. Valle Seco, Valles Caldera National Preserve, New Mexico. Reproduced with permission from *The Plug and Pond Treatment: Restoring Sheetflow to High Elevation Slope Wetlands in New Mexico* by Bill Zeedyk and Steve Vrooman

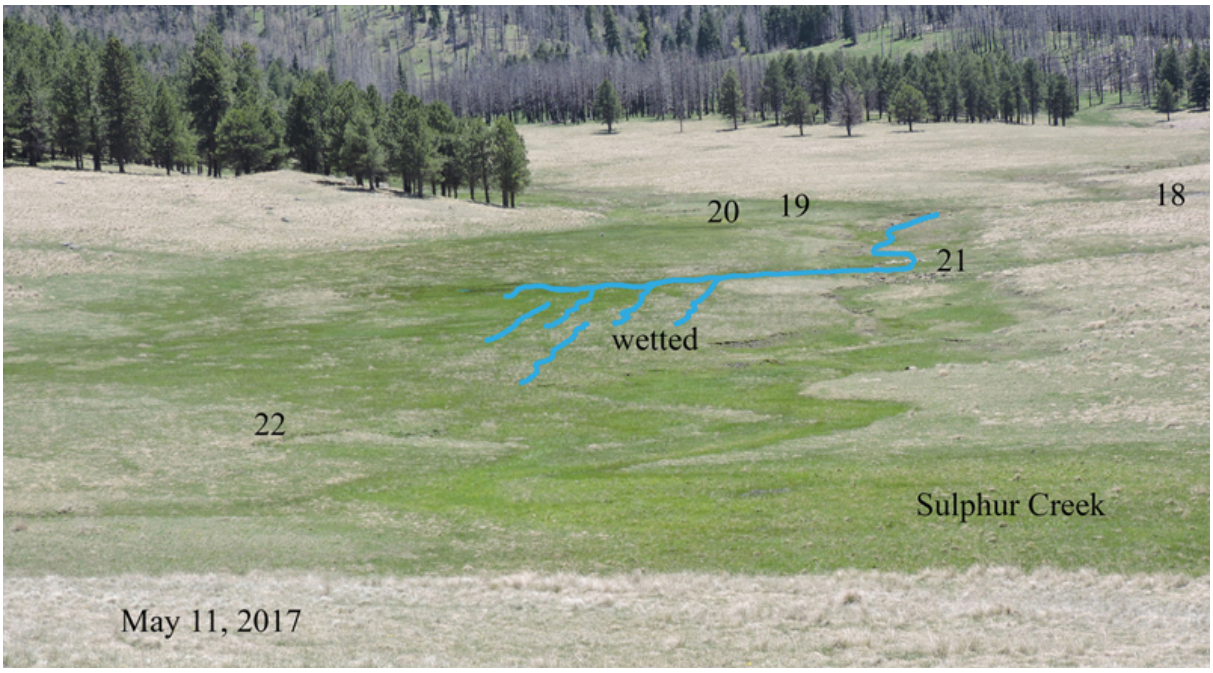


Fig. 9.21B. A new *plug and pond* was installed at Site 21 during October 2016 and successfully rewetted the central portion of the meadow. The area below Site 18 is also beginning to respond to treatment. Credit: Bill Zeedyk. Reproduced with permission from *The Plug and Pond Treatment: Restoring Sheetflow to High Elevation Slope Wetlands in New Mexico* by Bill Zeedyk and Steve Vrooman

Fig. 9.22. In the left image, Nina's Spring's flow has been captured by, and channelized within, an abandoned and gullied wagon road on the north side of San Antonio Creek, Valles Caldera National Preserve, New Mexico, leaving the original flow path dry, 2009, © Google™ Earth. In the right image, a *plug and pond* has rerouted the flow path out of the gully and back onto the natural alluvial fan, respreading the water to regenerate a wet meadow over a much

larger area, 2017, © Google™ Earth. Reproduced with permission from *The Plug and Pond Treatment: Restoring Sheetflow to High Elevation Slope Wetlands* in New Mexico by Bill Zeedyk and Steve Vrooman

MULTIPLE FUNCTIONS OF DIVERSION SWALES

DIVERSION SWALES AS RAIN GUTTERS IN THE LANDSCAPE

Maasai in the Laikipia Plateau, Kenya, harvest runoff from roof-like rock outcroppings by using masonry diversion swales to direct the water to cisterns (fig. 9.23). That water can then be used for domestic and agricultural uses, while eliminating the need for villagers to walk 12 miles (20 km) to fetch water.

Fig. 9.23. Runoff from large rock outcrop diverted to 79,000-gallon (300-m^3) cistern. Lapikia District, Kenya. Search "Harvesting Rock Water" at HarvestingRainwater.com for more of the story

DIVERSION SWALES USED TO "DAYLIGHT" FORMERLY CULVERTED OR BURIED WATERWAYS

"Daylighting" is the act of uncovering a piped or buried waterway and restructuring and revegetating it to make it a healthy, meandering, more natural watercourse. Daylighting reverses the pattern of channelizing and burying our natural waterways, a practice common in the built environment. The success of

the 1984 daylighting of Strawberry Creek at a park in Berkeley, California, inspired numerous daylighting projects in other communities.[19] The benefits include flood control, increased groundwater recharge, biofiltration of stormwater, enhanced wildlife habitat, and increased neighborhood livability, as you can see when you compare figs. 9.24A and 9.24B. For more information on daylighting techniques and restoring waterways in urban environments see the resources in appendix 4.

Fig. 9.24A. Before. Waterway is culverted and buried under this road. Los Angeles Eco-Village, Los Angeles, California

Fig. 9.24B. After. Previously culverted and buried waterway is now uncovered and daylighted in a block of city street that has been converted to a neighborhood park. Los Angeles Eco-Village, Los Angeles, California

THE BERMS OF DIVERSION SWALES AS ROADS OR PATHS

The berms of small-scale diversion swales can be constructed to function as paths. The berms of large-scale diversion swales can be constructed to function as roads. To ensure the roadway/berm does not become saturated with infiltrated water, it should be constructed with a well-compacted base of good draining soil (engineered fill dirt composed of gravel and sand, or appropriate local materials). Fig. 9.25 shows driving, biking, and pedestrian access ways on raised diversion-swale berms, with plants in the basins harvesting runoff. For further information on road construction, see appendix 4.

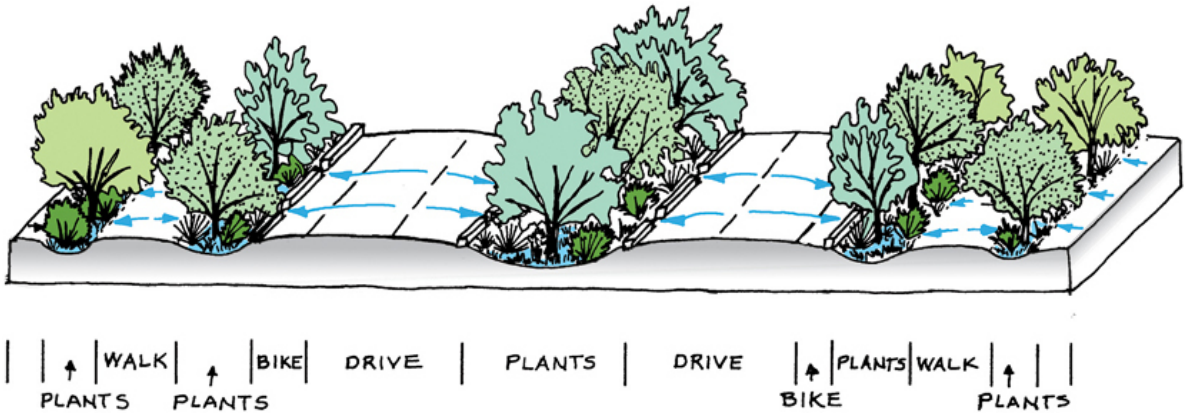


Fig. 9.25. Raised berm access ways and sunken basin planting areas

KEYLINE PATTERN CULTIVATION

For those who want to understand more about how to read the landscape and learn more keylinebased strategies that use this understanding, see resources on *keyline design* in appendix 4. Many aspects of keyline design apply to farm and ranch water management, including siting and constructing small earthen dams and ponds. One strategy of particular interest is keyline cultivation. In landforms of undulating hills and valleys, *keyline cultivation* directs water out of wetter valleys onto drier ridges. This is done by plowing slightly off contour so that each subsurface furrow slopes and directs water gradually away from the valley toward the center of bordering ridges (figs. 9.26 - 9.28). To implement this strategy, non-subversion rippers—such as keyline plows—are used. According to keyline design consultant and author Ken Yeoman, keyline cultivation … "delays the arrival of runoff water in the valley shapes and holds it longer on the ridge shapes, giving rainfall more time to soak in. Keyline pattern cultivation thus improves the field capacity of the soil by balancing water storage in the soil across the whole landscape. This unique pattern of cultivation greatly reduces the typical syndrome of dry hard ridge and over wet, if not eroded, valleys."[20] But the devil is in the details; so to make this cultivation pattern work you must read the comprehensive key-line resources in appendix 4.

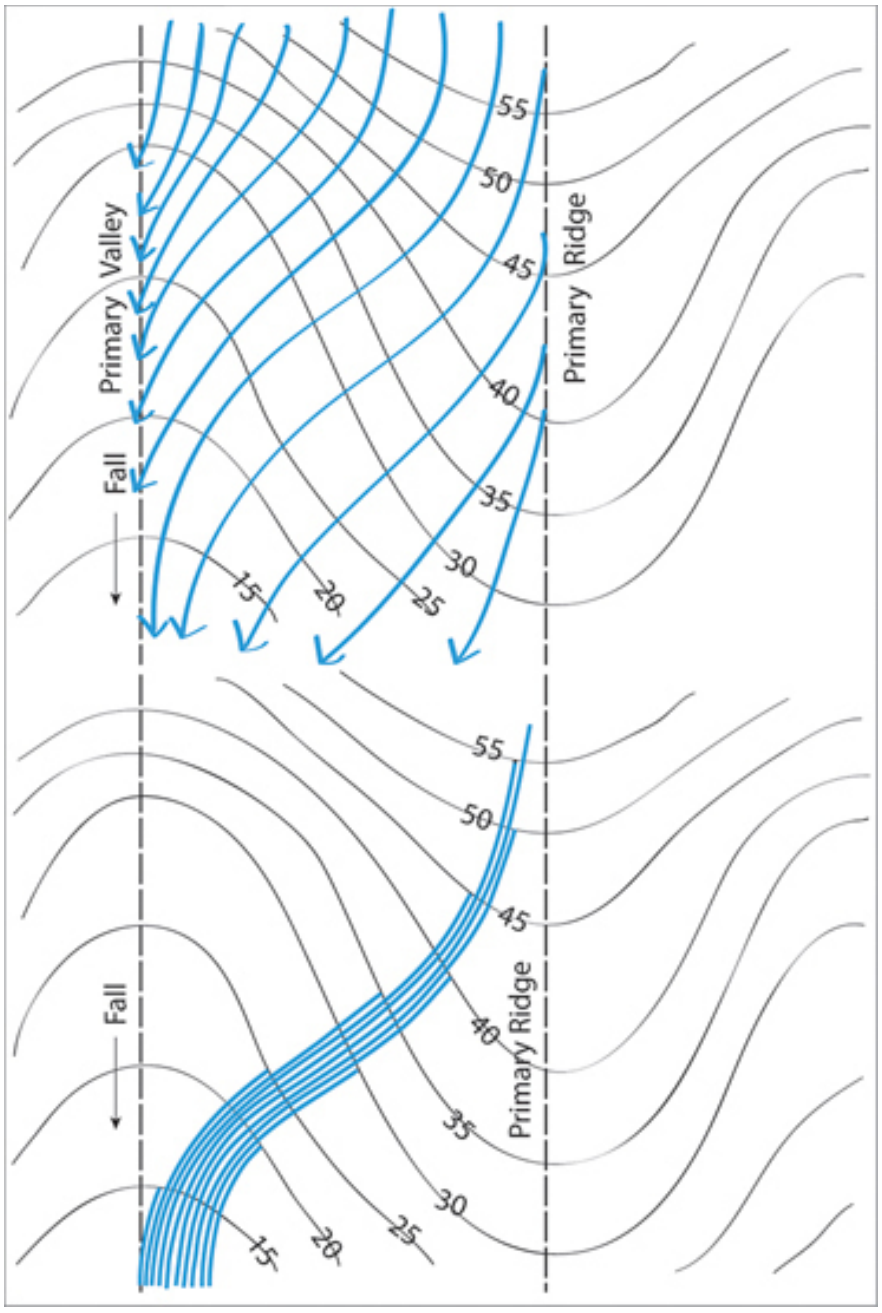


Fig. 9.26. Water flow direction and volume in a typical foothills landscape with water flowing from primary ridges to primary valleys down the fall of the slope.

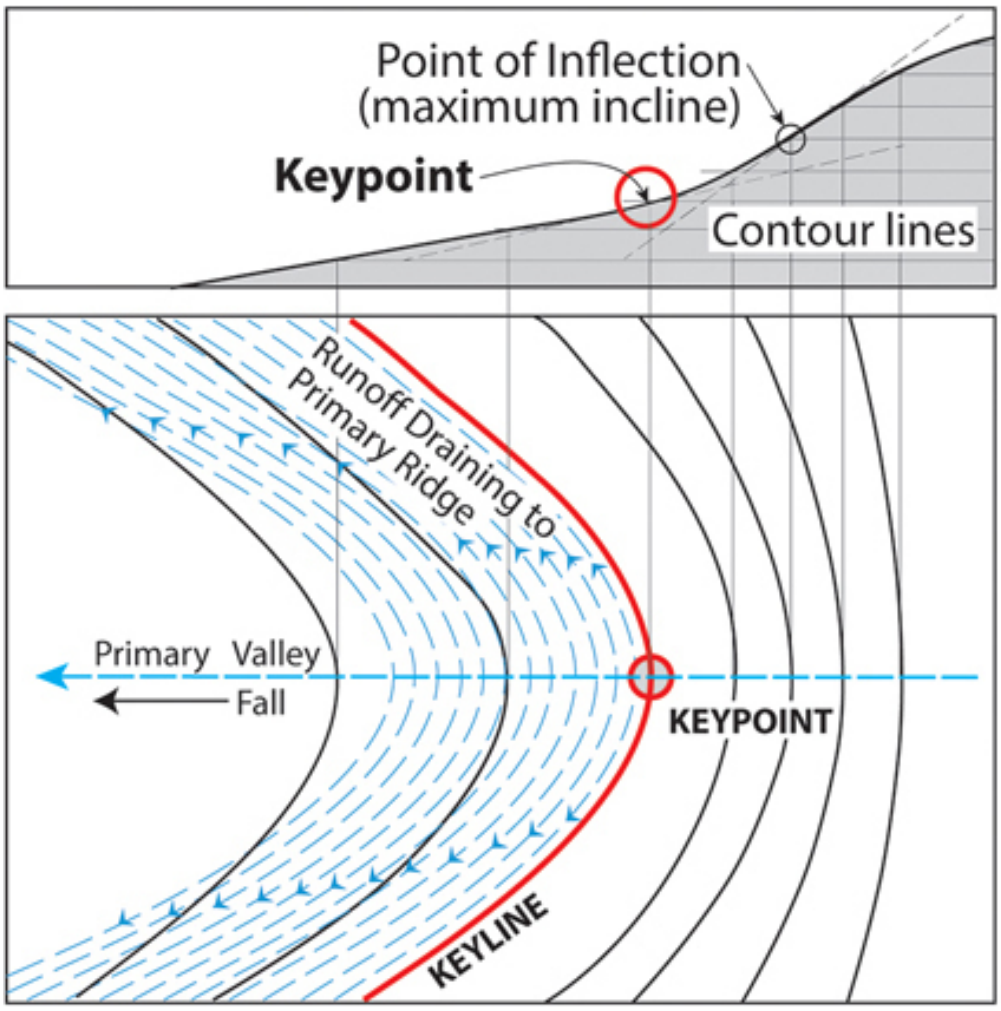


Fig. 9.27. Top: The primary valley keypoint is not at the point of inflection (a common mistaken understanding), but where the valley starts to flatten. Bottom: Keyline pattern of cultivation lines that run parallel to the keyline show how runoff water can flow from a primary valley out toward the primary ridges, opposite to normal gravity flow shown in fig. 9.26. This process markedly decreases the speed of runoff from a landscape and increases the amount of water infiltration in that landscape, improving soil quality and pasture/plant growth. Images and captions reproduced with permission from *Regrarians eHandbook*, Geography chapter, by Darren J. Doherty and Andrew Jeeves

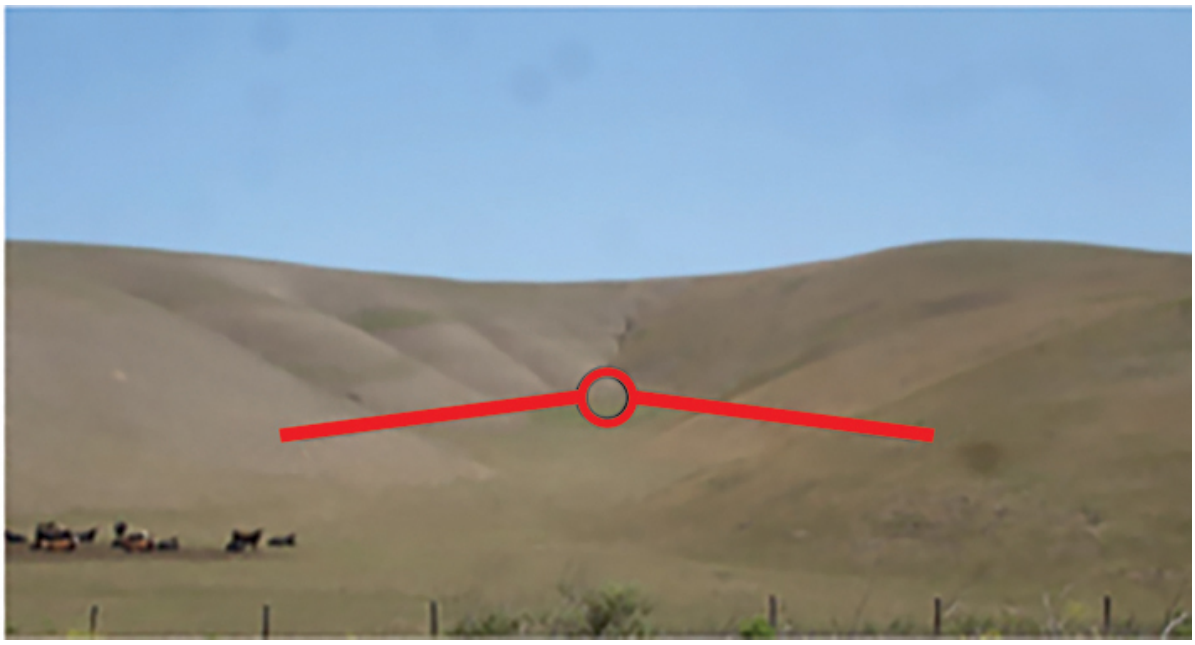


Fig. 9.28. Circle identifies keypoint in this landscape. Lines identify keyline in the landscape. Photo by Darren J. Doherty. Reproduced with permission from *Regrarians eHandbook*, Geography chapter, by Darren J. Doherty and Andrew Jeeves

REAL-LIFE EXAMPLES OF DIVERSION SWALES

SNOW DIVERSION BERMS HARVESTING WATER WITH WATER— FLAGSTAFF, ARIZONA

When the snowmelt began to flow down John Taylor's street in Flagstaff (average annual rainfall of 20 inches or 524 mm at 6,911 feet or 2,107 m elevation) he would quickly construct a diversion swale snow berm to redirect the runoff flowing along the street curb to the rain garden basin in his yard. This harvested thousands of gallons of free water (snow-melt) using water (snow berm), and did not require a permit because it is so ephemeral—requiring just 20 minutes of play keeping the berm intact as the basin filled (figs 9.29A, B).

Fig. 9.29A. A snow berm redirects snowmelt from street curb into yard. Credit: John Taylor

Fig. 9.29B. Snow berm diversion swale empties into a rain garden that will erupt with vegetation once spring arrives. Credit: John Taylor

The whole system acts as an "eddy" or "backwater," so once the basin fills, water backs up to the inflow point. No more water will enter the basin until the water already in it infiltrates, making room for more water to enter.

Good follow through was a must. Had John simply built the snow berm and walked away from it, it would have resulted in a dangerous ice slick over the sidewalk on a freezing night. Thus he always stood by to personally monitor the flow and he thoroughly cleared the berm after he was done playing, making sure the sidewalk was totally clear and free of water and ice.

Luckily his neighborhood street was not salted to melt snow and ice (the salts—unlike volcanic cinders—harm soil and plants). But if his street had been salted, he would have waited for the initial runoff to wash away the salts before beginning to divert water into his yard. Then he would have monitored the effects before doing it again.

The water harvested within the mulched basin infiltrates deep into the soil and lasts for weeks into the dry windy spring, enabling John's landscape to thrive "irrigation-free."

Beyond the benefits of harvesting water, John says, "This was fun! It was a joyful activity where I played with my son, benefitted from exercise, fresh air and dialogue with neighbors. I also learned about the way water behaved on my property by watching this large inflow of water."

Via his non-profit TerraBirds.org, John has taken his learning to his new home and spread it throughout the community, creating irrigation-free water-harvesting landscapes at schools, churches, museums, and public building landscapes using crews of working/learning youth.

SPREADER DRAIN TURNING A STORMWATER LIABILITY INTO AN ASSET—MORIARTY, NEW MEXICO

By Chris Meuli

In 1996, an opportunity arose to create a spreader drain on my gently sloped (1–3% slope), undeveloped 20-acre (8-ha) site in Moriarty, New Mexico, where annual precipitation averages 14.5 inches (368 mm) at 6,217 feet (1,894 m) elevation. One day after a heavy summer rain, I almost got stuck in this high-plains desert while driving on what previously had been very dry soil. A neighbor had started developing a subdivision uphill from my site. The bar ditch next to his new gravel road had collected the surface water from over 50 acres (20 ha) of land and concentrated it on my site, creating a quagmire.

Seeing this over-concentration of a resource (the "pollution" of water in the desert!), I began considering ways to spread it over a much larger area, rather than allowing it to concentrate in a useless mud hole or cause an eventual washout. I

learned that the county engineer was requiring my neighbor to put a 24-inch (60-cm) culvert under the future road that would connect to this new gravel road. I approached my neighbor to see if he would place a culvert where it would benefit both of us. He agreed. I located a spot where the bar ditch water could easily be directed into a culvert and delivered onto a corner of my property as high as possible in the landscape. This would become the head of the spreader drain.

Since I didn't know how to slope this drain, I read up on it in Bill Mollison's *Permaculture: A Designer's Manual* and found more than a page on spreader drains and related earthworks. He suggested that swales be built to slope in the range of 1:600 to 1:1,500 (a drop of 0.8 to 2 inches in 100 feet) on most soils and up to 1:6,000 (a 0.2-inch drop in 100 feet) in areas with fine sands.[21] I guessed that a slope of 1:1,200 (a 1-inch drop in 100 feet or 1-cm drop in 12 meters) on my heavy caliche-clay soil would suffice.

Siting the spreader drain

I began the work by hiring two neighborhood boys, 10 and 13 years old, to help do the bunyip work (see appendix 1). They marked a 700-foot (213-m) long level contour line starting at the outflow point of the future culvert, and placed pink highway flags every 25 feet (7.6 m) along its length, making a nice pink curve that could be seen easily from a distance. I knew we had an accurate contour because the flags formed a curving line that matched the subtle topographical variations in the landscape. We reset several flags that didn't fit into the general curve due to minor local variations, so that the curve became broad and gentle (fig. 9.30).

Fig. 9.30. The first step in laying out a spreader drain: Chris Meuli's young neighbors (and their dog) use a bunyip to lay out a contour line across a 3% slope on Chris' property. Credit: Chris Meuli

Next we used the bunyip water level to mark the sloping line of the diversion swale just downslope of the contour line. Starting from the 100-foot (30-m) contour flag, we used the water level to mark a point 1 inch (2.5 cm) lower than the main contour line and placed a sentinel flag there. At the 200-foot (61 m) contour flag we found where the slope dropped 2 inches (5 cm) and placed another sentinel flag, and so on—marking the spreader swale's sloping path with a progressive drop in elevation of 1 inch every 100 feet or 1:1,200. We could see that the row of sentinel flags pulled away gradually from the contour flags, going imperceptibly downhill just as we would expect the 1:1,200 slope to pull away gradually from the level contour. Then we eyeballed both curving lines and placed flags every 25 feet between the sentinel flags so they mirrored the gentle curves of the contour flags uphill (fig. 9.31). The last 200 feet of the drain were marked level. That done, we pulled out all the flags that were on the level contour.

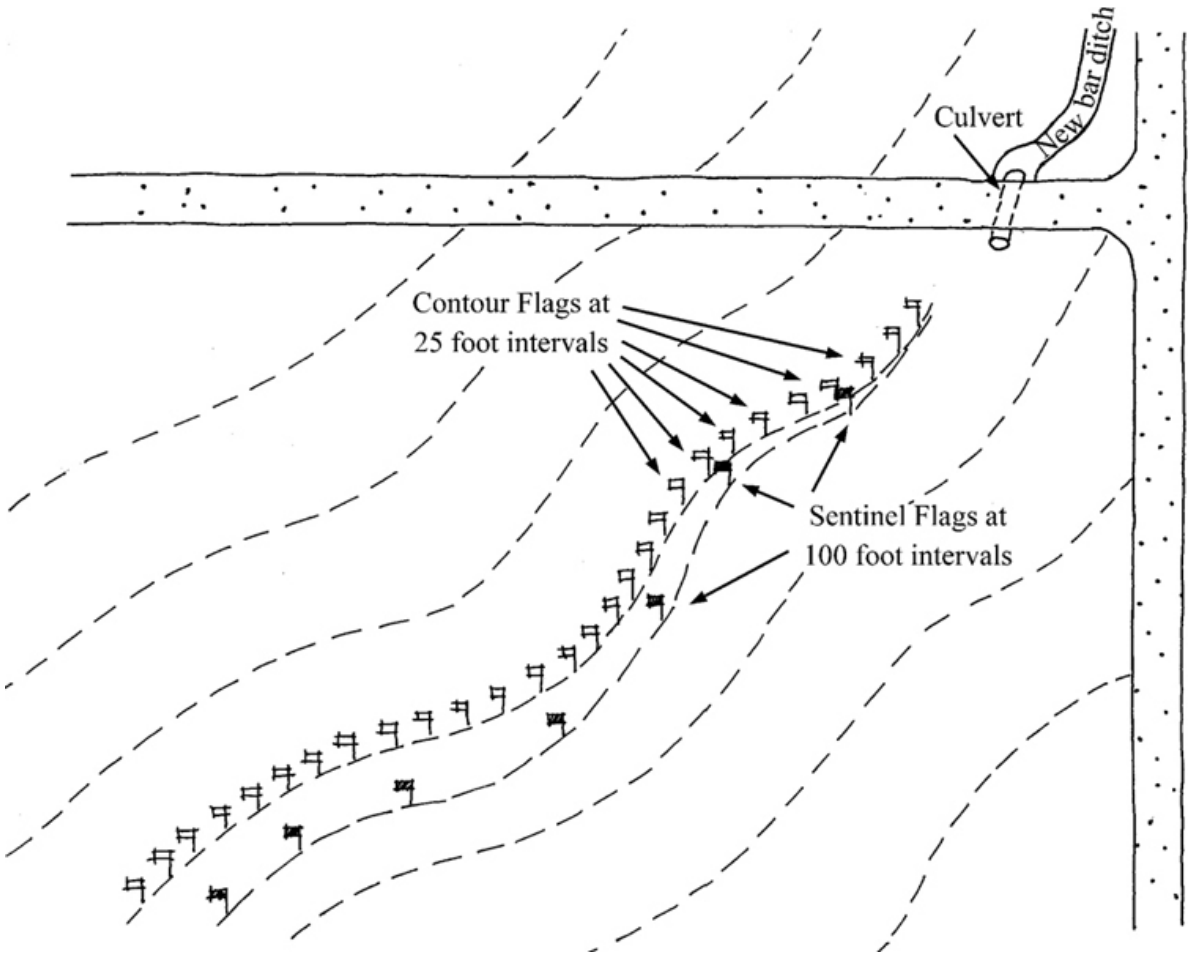


Fig. 9.31. Marking the spreader-drain route

Building the drain

To move the dirt, I hired my neighbor's road grader operator, who was doing excellent, but conventional, work on the new gravel road. When I described the plan, he knew "exactly" what I wanted, and would have been happy to do the work without me being present! When I met him the next week to supervise the project, he was totally surprised at what I really planned to do. He had been doing excavation work for over 20 years and didn't believe you could move water without having a big ditch somewhere. We began by grading deeply into the soil upslope from the flags, throwing the dirt uphill with the grader blade. On the return trip, we would throw that dirt farther uphill creating a V-shaped furrow almost 16 feet (4.8 m) wide. After 5 hours, we had thrown over 300 cubic yards (228 m^3) of dirt uphill (fig. 9.32)! This created a drain with a center 11 inches (27.9 cm) lower than its overflow edge. We also had a fairly flat berm above the drain that was almost 1 foot (30 cm) high and over 12 feet (3.6 m) wide.

Fig. 9.32. Grader cutting diversion swale on Chris' land. Note: The operator was not allowed to drive the grader on the downslope side of the swale to prevent damaging any soil-stabilizing vegetation over which the swale overflow water would flow. Credit: Chris Meuli

Figs. 9.33A, B, C, and D are elevation views of the slope before and after Chris' spreader-drain construction. Arrows denote slope.

Fig. 9.33A. Original slope. Drain location marked with flagging pre-construction.

Fig. 9.33B. Early passes with road grader. Digging commenced, dirt cast upslope.

Fig.9.33C. Drain with basin dug upslope of flagging and dirt cast upslope of basin to form berm. Final drain size 11 inches (30 cm) deep, 16 feet (4.8 m) wide.

Fig. 9.33D. Completed drain. Uphill berm graded to form road, downhill overflow apron is undisturbed.

With a spreader drain, there is a tradeoff between how much capacity the drain should have so the water can soak into the earth locally, and how much water is allowed to overflow the apron at the low end of the drain on the downslope side. This is determined by the slope of the land (the steeper the land, the greater the volume of water the spreader drain should hold), and the area of land being serviced (the larger the area, the more water should overflow the apron).

Ideally, the overflow apron downslope from the flags (marking the spreader drain's route) is grassed, remains undisturbed, and is not compacted. All this greatly reduces the chance of erosion. I carefully supervised the road grader operator, making sure that he made his turnarounds upslope from the spreader drain to minimize disturbance of the intact vegetation.

The spreader drain was an enormous and beautiful piece of meandering earthwork, wandering through the landscape like a fat brown snake lying in the gray buffalo grass. Its natural appearance amazed even the grader operator. He later commented that the dirt thrown uphill would "make a dandy road" that would never get muddy.

Working with watershed neighbors

The magnitude of the work alarmed my neighbor, who immediately called in several civil engineers, who all told him it was going uphill and would never work anyway because it wasn't deep enough. He had his lawyer draw up a contract absolving him of all liability regarding the spreader drain. Whenever the document referred to "accepted civil engineering practices" I added "and sound permaculture design." We both signed it and he filed it with the county clerk. It

was a thoughtful design that optimized natural patterns, utilized a "waste product" in a beneficial way, and incorporated features to prevent disaster. I was surprised to realize that conventional "earthworkers" didn't use these common sense principles in their work.

The next week I checked out the promised 24-inch (60-cm) culvert. I was aghast to discover that its crown was 36 inches (91 cm) below grade! It took me two weeks to calm my disbelief before calling my neighbor to learn his rationale. He stated that the civil engineer recommended 18 inches (46 cm) of packed dirt and 18 inches of gravel above the culvert. The process of planning a road from the top down, rather than considering gravity, water, and landform as primary, puzzled me. I told my neighbor that it was only a matter of time before the culvert would silt in and need to be replaced. He listened skeptically.

Then I created a simple surge basin below the culvert to absorb the energy of the incoming water before it entered the spreader drain. A surge basin is a pond, often 12 to 18 inches (30 to 45 cm) deep that utilizes the standing water in the pond to diffuse the kinetic force of the incoming water. This prevents the scouring so often seen in arroyos and below culverts. A surge basin has an overflow sill that should be level with the inflow of the channelized water or the bottom of the culvert. Optimally the surge basin turns the water 30˚ or more before allowing it to enter the head of the spreader drain in an even and controlled manner. The water flow is turned by building the spillway of the surge basin at an angle 30˚ or more from the channeled inflow to the basin.

The spreader drain in action

The first spring after the swale's construction, over an inch (25 mm) of rain fell on soil that was saturated by unusually heavy snows. The spreader drain worked beautifully, gently distributing a tremendous amount of surface runoff in a thin film of water along its entire 700-foot (213-m) edge, soaking areas 300 feet (91 m) downhill (nearly 5 acres or 2 ha). I was able to document this marvelous event with photographs, capturing this remarkable apparition of a sinuous body of water in the high-plains desert (figs. 9.34A, B). Three years later the culvert under the road silted in and only these pictures would finally convince my neighbor that the water was really not running from the spreader drain back up into the culvert. He paid for a new culvert and replaced it, again at the same depth (he still didn't get it!), and I paid to have it reset 18 inches (45 cm) higher.

Fig. 9.34A. Diversion swale harvesting runoff, April 1997. Arrow points at same tree in both photos. Credit: Chris Meuli.

Fig. 9.34B. Same diversion swale as in fig. 9.34A. This photo taken in September 2013. Credit: Chris Meuli.

The next year I planted a crenulated windbreak downhill from the spreader drain. Due to water harvested in the soil of the spreader drain from the previous spring, I found the ground 70 feet (21 m) downslope to be easy digging and still moist at a depth of 2 feet (0.6 m), an unbelievable change from the previous 12 years. The windbreak's trees are thriving, and I have not had to water them since planting, despite increasingly dry weather over the past several years in New Mexico. Grasses and weeds have sprung up in the drain itself. I had wondered if they would impede the flow of water and cause damming and excessive silting, but the flows are so slow and broad that this has not occurred. And the road above the drain is an excellent road indeed (fig. 9.35).

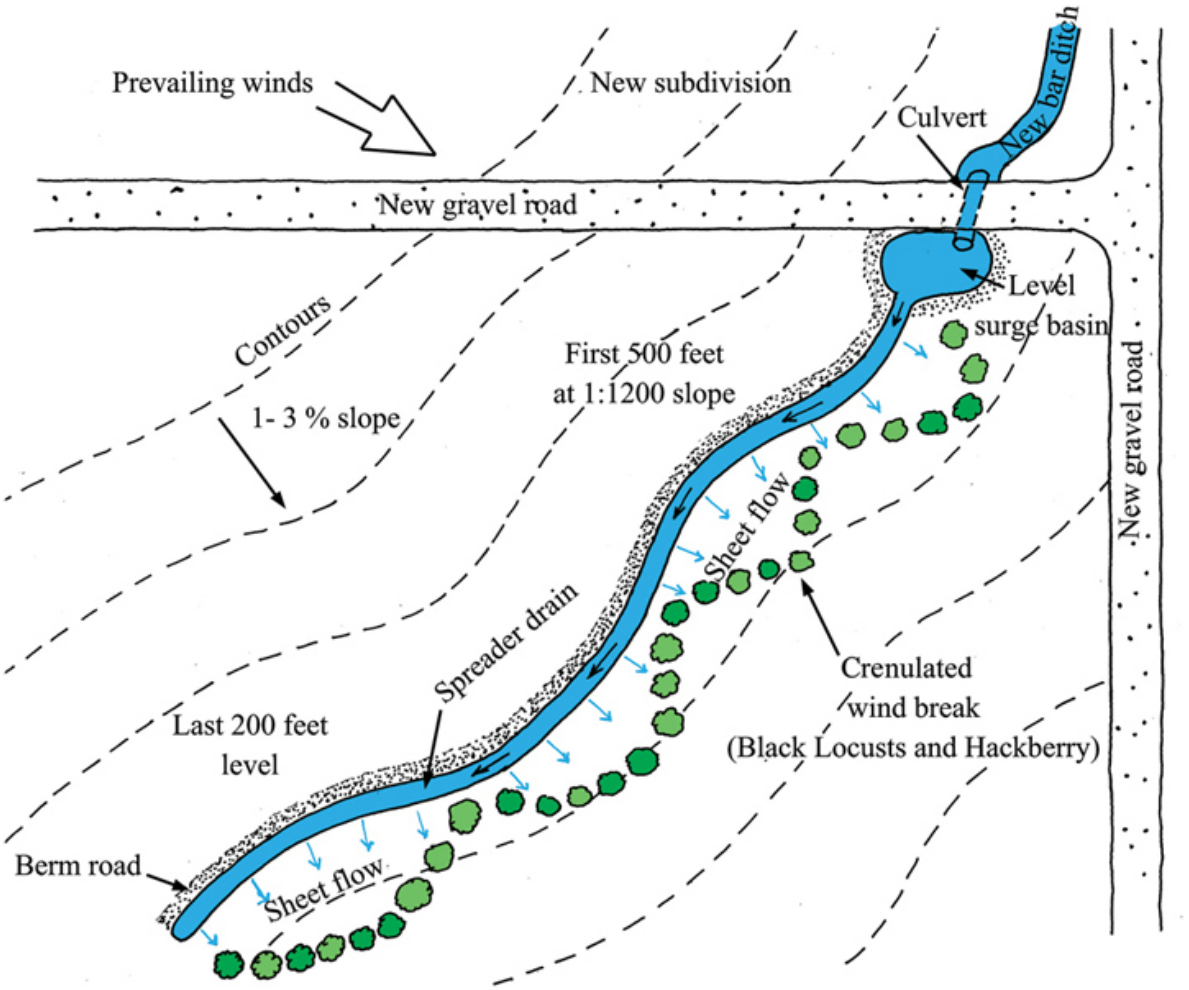


Fig. 9.35. Completed swale, surge basin, and windbreak layout

The feedback loop

Despite the swale working well, Chris would make the slope of his diversion swale more gradual if he were to do it again. He has noticed that water runs quickly within the first 200 feet (60 m) of the structure, where signs of erosive channelization are just beginning to show. If the swale sloped more gradually, 1:2,000 to 1:3,000, this likely would not have occurred. To remedy the situation, Chris plans to enlarge the surge basin and reduce the slope of the first 200 (60 m) feet of the swale.

The above was written by my friend Chris Meuli, with much of it based on his article "Capturing and Using Wild Water: The Well-Built Spreader Drain" published in the Permaculture Activist, Nov. 2000 issue.

See chapter 3, Real-Life Examples, Windberm Story, for contact information for Chris Meuli.

USING FARM FIELDS, VINEYARDS, AND ORCHARDS AS GROUNDWATER-RECHARGING, FLOOD-ABATING

FLOODPLAINS

In the winter, when his dormant crops didn't need water and the river was flowing high with winter rains, farmer Dan Cameron tried something different—he went to the nearby river and opened an irrigation gate. Water poured down a canal and flooded hundreds of acres of his vineyard where it could infiltrate into the soil and seep down to the aquifer. He kept this up from February to May.[22]

His idea was to recharge the dwindling groundwater table, which he and his neighbors southwest of Fresno, California, had been pumping and depleting for the past 35 years. It worked.[23]

Perhaps in the abundance of the winter rainy season, Dan and other farmers could even give more water back to the aquifer than they had taken out in the dry season and droughts. At the same time, they could reduce downstream flooding in times of intense flow, and maintain flows to downstream areas and ecosystems in dry times and drought.

That potential sparked new research, including that by Helen Dahlke, a water specialist at the University of California, Davis, who worked with farmers growing almonds, pistachios, and alfalfa who wanted to do the same as Dan.[24]

According to National Public Radio (NPR), "In theory, California's aquifers could hold more than twice as much water as all of its dams and manmade lakes. And Peter Gleick, a water expert and co-founder of the Pacific Institute, says there is enough water runoff available after winter storms to recharge those groundwater aquifers."[25] In addition, unlike the surface storage of water behind dams and in lakes, far less water stored in underground aquifers is lost to evaporation.

For more on this strategy, search "Flood-MAR" or "Flood Water for Managed Aquifer Recharge" online.

DIVERSION SWALES IRRIGATING LANDSCAPES AND CONTROLLING STORMWATER—DAVIS, CALIFORNIA

At Village Homes in Davis, California, (average annual rainfall of 19 inches or 482 mm), residential lots and streets are graded to slope toward meandering, creek-like swales that run through the development. Runoff caught within these swales passively irrigates a beautiful landscape of shrubs and trees lining the swales (fig. 9.36). Small check dams are placed across these drainages to help slow the flow of water, harvest more runoff in the soil, and prevent surges downstream. The effect is amazing. As developers Judy and Michael Corbett report, "In light rains,

this surface drainage system allows all the water that falls on site to be absorbed into the ground. In heavier rains, the system empties some water into the city's storm drains, but not nearly the amount a typical subdivision would. Currently, at least 90 percent of on-site runoff is kept on site. And as the trees continue to make the soil more porous, the land's capacity to hold and absorb runoff increases."[26] See appendix 4 for a resource.

Fig. 9.36A. Elevation view of Village Homes houses and fruit tree-lined diversion swale between them. All works great, although much more water could be harvested if there were also rain gardens in private yards above the public diversion swale. Note how homes front or face the pedestrian/bicycle/water corridor, not the street, to encourage more public interaction and communal stewarding of the corridor. Reproduced with permission from *Designing Sustainable Communities* by Michael Corbett and Judy Corbett

Fig. 9.36B. Plan view of Village Homes. Diversion swales intercept runoff from streets, irrigate the landscape, and meander along with bicycle/pedestrian paths past homes' yards. All homes oriented to maximize passive solar heating and

cooling. Reproduced with permission from *Designing Sustainable Communities* by Michael Corbett and Judy Corbett, Island Press, 2000

DAYLIGHTING A ONCE BURIED RIVER— SEOUL, SOUTH KOREA

Seoul is a very dense and bustling city whose many loud, car-filled streets left me craving the beautiful calm of nature. Then, in the center of the city, it suddenly appeared—the 6 mile- (10km-) long oasis of the Cheong Gye Cheon Stream (though it is, by southwestern U.S. standards, a river and I'm calling it such). It had been buried in 1958 as part of an effort to remove temporary housing built along its banks after the Korean war, then was further covered with an elevated highway in 1976 (fig. 9.37A). But happily, in 2005 it was daylighted and reborn (fig. 9.37B,C).

Fig. 9.37A. Pre 2005, the Gheong Gye Cheon River buried underneath an elevated highway. Photo is part of a historic photo tile mosaic along the now daylighted river.

Fig. 9.37B. A bridge built in 1410, in the background, was rediscovered and renovated when the river was daylighted here beside city hall. Modern footbridge in the foreground.

Fig. 9.37C. The now daylighted Cheong Gye Cheon River in 2007. Three piers of the now demolished highway remain as a reminder of the river's previous burial.

I dropped down onto the well-vegetated bank-side pedestrian paths, which on the weekends are packed with joyful people—the river park attracts an estimated 60,000 visitors a day (fig. 9.37D).[27] Fish, birds, and dragonflies abounded. Children played in the water and jumped from rock to rock. Couples were getting married. Orchestras and bands played under the bridges. Public art was everywhere. And history had been unearthed and spotlighted, including a pedestrian bridge built in 1410 that was now fully renovated and back in use.

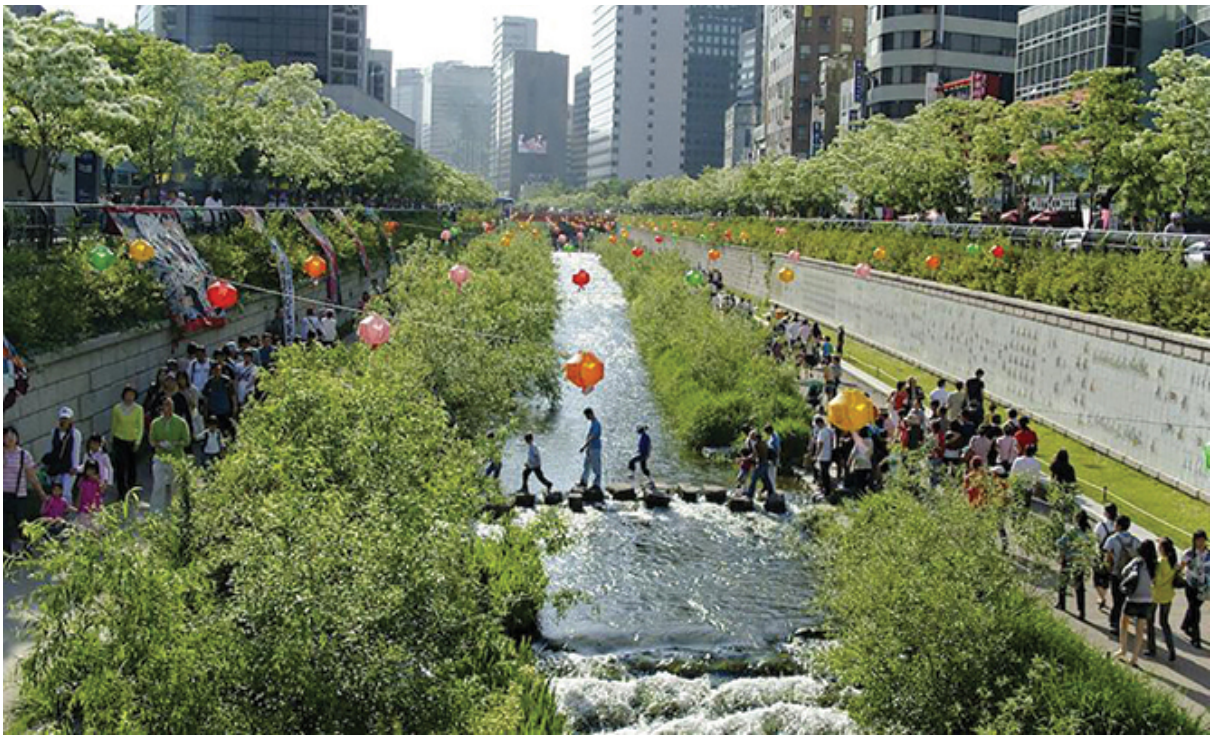


Fig. 9.37D. After daylighting river. Gheong Gye Cheon River Festival in 2008. Photo © Michael Sotnikov, https://www.flickr.com/photos/stari4ek/

With camera in hand, I spent the next two weekdays exploring. I discovered many quaint neighborhoods while strolling along the river and the many small tributaries that had also been daylighted and brought back to life. The revived tributaries and river are now the core of a path network throughout the watershed, and they help manage and clean stormwater while reducing flooding.

This was the highlight of my trip. I couldn't get enough of these corridors of life filled with water, people, culture, and nature. Unlike the noisy, auto-dominated streets above that drained me, these corridors enlivened the city, the country, and me.

The Cheong Gye Cheon River is an example that can inspire similar life-embracing transformations all over the world at many scales.

CHAPTER 10

In-Channel Strategies

A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community.
It is wrong when it tends otherwise.

—Aldo Leopold

Previous chapters primarily cover strategies used outside of water channels, where water flows across broad surfaces and tends to be spread out, shallow, and slow moving. This is called sheet flow. This chapter covers patterns, principles, and strategies used *within* water channels having a bed and banks, where greater volumes of water flow deeper and faster than flow outside of channels. The focus is on water channels having ephemeral flow (only hours or days—not more than 30—following rainfall) or intermittent flow (more than 30 days, but less than a year) flows, rather than channels with perennial (year-round) flow.

Building on the natural patterns presented in chapter one, (e.g. the erosion triangle) and others in Volume 1, appendix 1, we begin by observing and learning additional patterns in the in-channel context. The patterns and principles described here help you understand the components and natural workings of waterways. Patterns reveal how disturbances to natural conditions can result in degradation of waterways, and how nature tries to heal them. We use principles informed by these patterns to select and adapt strategies and approaches that will mitigate unhealthy erosion and/or dehydration in channels.

The strategies described here were selected because they are relatively easy to implement by hand, they typical use readily available on-site materials, and they are effective when placed and built right. Many other strategies are also available.

Do not approach a site with the goal of applying a specific strategy. This is like a "solution" looking for a "problem" and can create more problems—like trying to

fit a square peg into a round hole. Instead focus on understanding what is happening with the flow of water *and* sediment at your site and why it is happening, then determine an appropriate strategy. Said another way, keep asking the question, "What does the waterway (wash, creek, or river) want?" The more you understand how in-channel strategies affect—and are affected by—natural patterns, the better equipped you will be to select, place, build, and hybridize strategies that work in sync with the patterns at your unique site.

LEARNING AND ADAPTING

Lessons learned from observing natural patterns, along with lessons learned from human successes (see box 10.1) and mistakes on projects, can help us form and evolve guiding principles to ensure we don't forget essential considerations when assessing sites and planning work.

Box 10.1. Ancheta Creek Restoration Case Study

Wetlands are among the most productive ecosystems in the world, comparable to rain forests and coral reefs[1] and they are declining. New Mexico has lost over 52% of its wetlands.[2] But simple strategies can bring wetlands back. One example is a 3.75-mile (6-km) stretch of the Ancheta Creek on Ancheta Spring Ranch near Silver City, New Mexico, elevation 6,600 feet (2,000 m), annual rainfall 14.7 inches (373 mm). The landowners hired consultant Bill Zeedyk to help mitigate the loss of two feet of topsoil and associated wetland vegetation along the creek. Much of the creek was eroded down to bare bedrock and flow was dramatically diminished. This was due to past overgrazing; on-going grazing by trespassing livestock; disturbance caused by below-standard dirt roads, livestock trails, and highway 152 (which parallels the creek); and a devastating flood (fig. 10.1). With the goal of reestablishing a living sponge of accumulating topsoil and riparian vegetation, Bill marked out 68 locations where structures would most effectively slow and spread the water flow. Van Clothier of Stream Dynamics then built the structures—primarily one-rock dams (ORDs) built with on-site rock.

The result was dramatic. Six years after the structures were built—coupled with better range management to minimize disturbance in the creek—sediment had backed up behind the structures and vegetation had grown in the accumulated soil. The result was a *regenerative* living system (see box 1.1) that grew the structures and increased their effectiveness (figs. 10.2 – 10.4). The grasses and riparian sedges now act as living combs through which water must pass. These capture fine-grained sediments more effectively than rock structures alone—which are generative but not regenerative (see box 1.1). The captured sediments, especially the fine-grained ones, are great at holding soil moisture longer. This enables more seeds to germinate, growing more living combs and more living sponges, which in turn capture more sediment and moisture to grow still more vegetation, and on it goes. Thus the regenerative living system keeps building on itself.

The vegetation has now overtaken and surpassed the work of the rock structures along much of the creek, regaining a foot of topsoil and extending the intermittent flow of the creek. Another layer of one-rock dams could now be placed atop the first to regain one

more foot of topsoil (fig. 10.3). So much moisture is harvested within the healthiest sections of the reestablished wetlands that vegetation is now growing up the slopes, following the moisture drawn up through capillary action (fig. 10.4).

Now if this inspires you, remember that different sections of an eroding waterway with different conditions will require different approaches, and read on.

Fig. 10.1. Much of Ancheta Creek was eroded down to bare bedrock before remediation work was undertaken

Fig. 10.2. Six years after implementation, sediment is caught upstream of a one-rock dam where it supports the reestablishment of grasses and sedges and detains moisture seeping downstream. Ancheta Creek, New Mexico

Fig. 10.3. Eight years after implementation, wetland vegetation is reestablished on a long stretch of Ancheta Creek and has overtaken the now hidden one-rock dams.
Note: trees are at edge of original floodplain, so more work is still needed to regain that lost soil

Fig. 10.4. Van Clothier standing atop a one-rock dam on Ancheta Creek, pointing at the grasses and sedges growing up the banks as they follow the moisture wicking upward from the reestablished, water-rich wetland below. Photo taken six years after implementation

These lessons remind us of how to collaborate with—rather than fight—natural systems, the effects we need a strategy or approach to achieve, and the key details that should not be missed. As a result, these lessons increase the benefits of our work and minimize failure.

Utilize the eight general water-harvesting principles described at the beginning of this book and additional principles provided in this chapter that are specific to in-channel work.

Feel free to evolve these principles and create your own as your knowledge and experience grows. These are not rigid laws—they are evolving guidelines. Take all of these into consideration as you determine your course of action.

PATTERN AND PRINCIPLE ONE
Guiding In-channel Strategies

Pattern: The health of a waterway is as strong as its connection to its floodplains

Natural waterways and the lands adjacent to them take on characteristic shapes. These shapes are created by the dynamic interaction of water, soil, rock, and vegetation. Shapes and terms shown in fig 10.5 are used throughout this chapter to explain why strategies are selected and how they function.

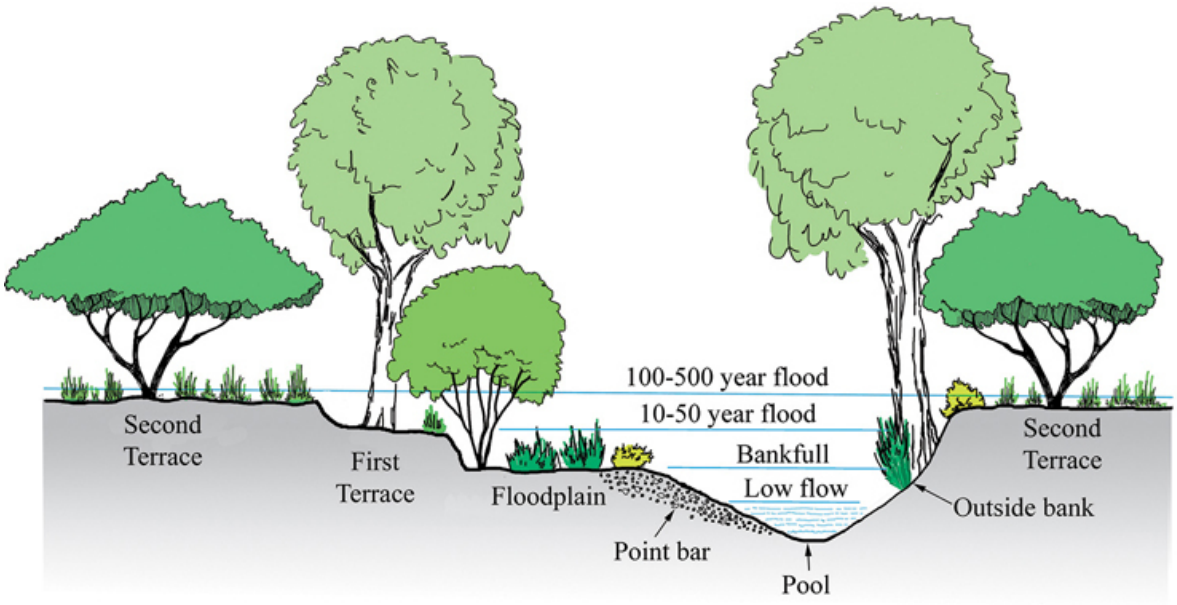


Fig. 10.5. Side view of a waterway and its floodplains. First terrace was the original floodplain before the channel downcut. Adapted from *Groundcover: A Handbook for Small-Scale Erosion Control in Coastal California*

The term "bankfull" refers to the water level that fills a creek or river channel to the top its banks (fig. 10.5). A bankfull water flow event occurs, on average, approximately every 1.5 years (though this may vary somewhat in different locations and climates). In large rain events, water levels may exceed the bankfull amount, flow over the banks, and flood across the adjoining floodplain. This has numerous benefits. The water spreads over more surface area, contacts more soil on the floodplain, and infiltrates into the soil. Water in the stream and on the floodplain infiltrates below to recharge shallow groundwater tables. As a result, the water table may still release water to the waterway's surface flows during subsequent dry seasons and drought.

Infiltration of water reduces the volume of surface flow during storms, reducing downstream flooding. The roughness of the vegetation growing on the floodplain slows the speed of flowing water, enabling more sediments and nutrients to drop out of the flow. This feeds beneficial floodplain life and improves the quality of surface water here and downstream. In very large storms and runoff events, high water volumes can fill up the lower floodplain and spread out onto the upper terraces (fig. 10.5), further slowing, spreading, and sinking the water flow.

Principle: Keep waterways and their flows connected to their floodplains

If connections between water flows and floodplains have been broken, reconnect them. Many of the strategies in this chapter help do just that. Floodplains are places for growing vegetation, not places for constructing buildings or other infrastructure that you don't want flooded.

Observe your waterways and compare them to others in your area. Are they healthy, deteriorating, or stabilizing? Even where there has been severe erosion, look for evidence of healing or stabilizing conditions such as accumulating soil or new growth of perennial vegetation. What is causing the erosion? What enables healing? Apply these questions and answers to conscious, effective actions.

For example, due to disturbance, a previously healthy meandering channel on which big flows could easily access the floodplain may become straightened or more channelized. This leads to increased steepness of the channel bed and increased speed, depth, and/or volume of water flow. This can in turn lead to erosive down cutting of the channel bed and potentially to disconnection of the channel from its floodplain (fig. 10.6). If people unconsciously compound the problem by further straightening and channelizing the banks with smooth concrete or other non-living material, this can further increase the speed of flowing water and erode the bed still deeper.

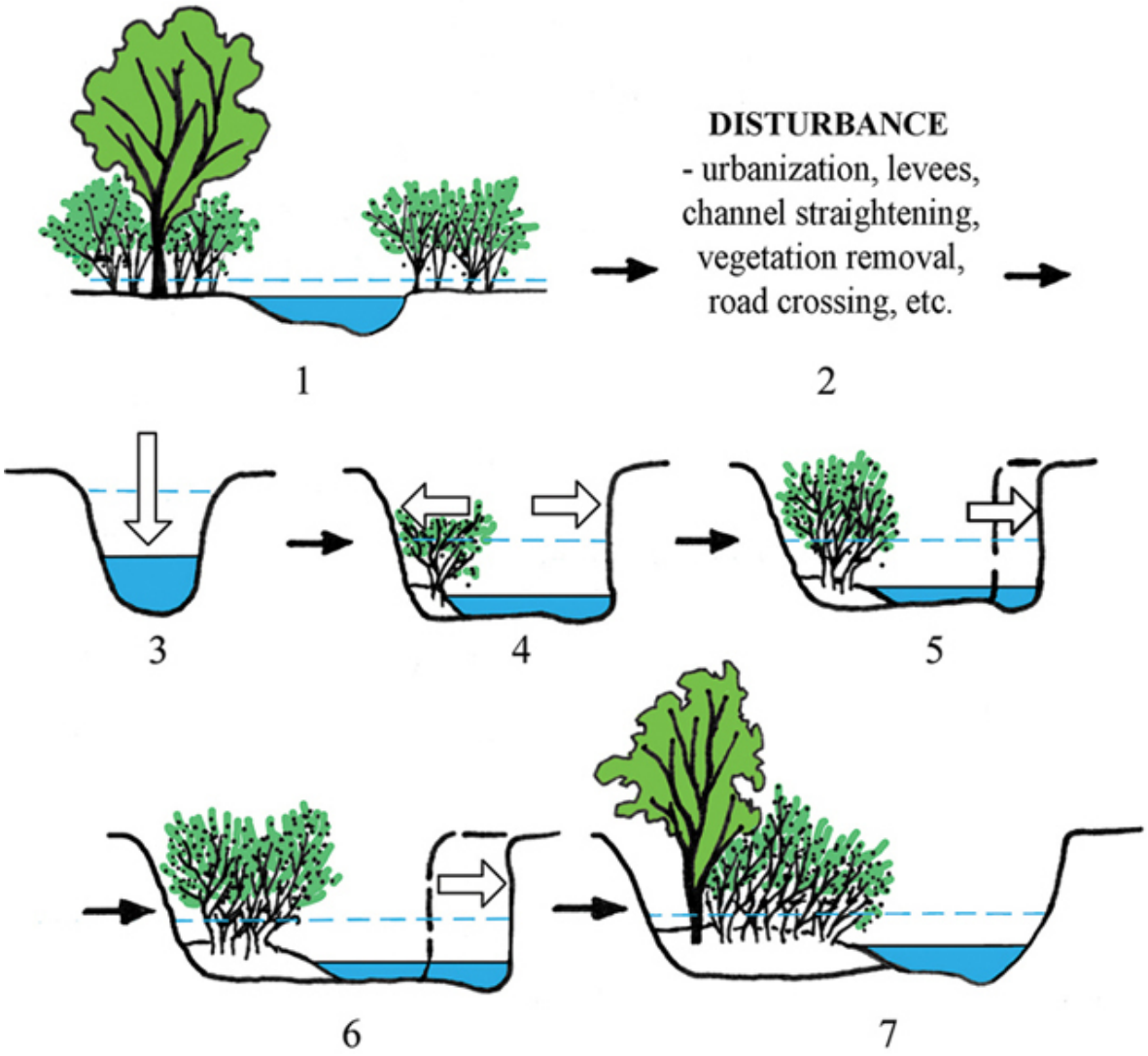


Fig. 10.6. Stable conditions deteriorate to unstable conditions, then evolve to stable conditions again. An erosive down-cutting gully with no access to floodplain results in full force of water's flow applied to the channel's bed (3). It later evolves into a calmer, shallower, widening water channel that creates a new accessible, vegetated, sediment-trapping floodplain by beneficially eroding its own banks as it establishes a more meandering path (7). The blue area represents *bankfull* or normal full-channel flows just before they would begin to spill over the channel's banks onto the floodplain, while the dotted horizontal line represents the depth of typical flood flows. Adapted from *Let the Water Do the Work* by Bill Zeedyk and Van Clothier

Sometimes erosion can help heal channel conditions, as shown in fig. 10.6. Here water flowing in a narrow, down-cut channel begins to heal the stream by eroding and widening its own channel. This enables the flow to meander more (see pattern

FOUR in this chapter), reducing the steepness of the channel bed, while at the same time forming and connecting with a new lower floodplain. Vegetation growth slows water flow further and traps more sediment. The formerly deepening bed of the channel stabilizes at its current elevation and could eventually even rise. The better we understand such natural processes, the better we can collaborate with and enhance them.

Surface water flows; vegetative cover; and the level, quality, and quantity of groundwater are tightly linked. Harming or helping one or more of these harms or helps the others (fig. 10.7).

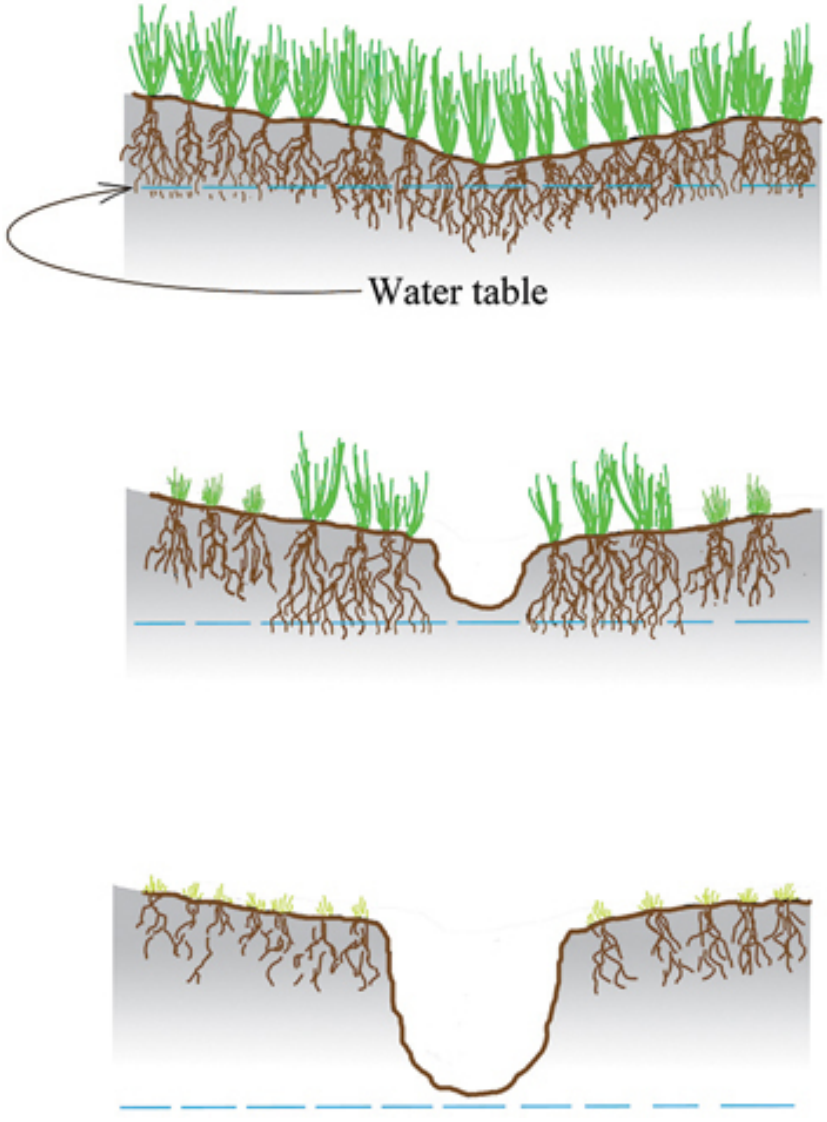


Fig. 10.7. The impact of vegetation, erosion, and a deepening gully on the water table and on one another

PATTERN AND PRINCIPLE TWO
Guiding In-channel Strategies

Pattern: Sediment size and distribution are "tracks" of the flow

Sediment can be anything from fine clay particles to large boulders, and this sediment moves—or "flows"—along with water flows. Always consider both water flow and sediment flow in design. The lower the velocity or energy of the flow, the smaller the size of sediments the water can carry. Steep, fast-moving rivers have enough energy to easily transport boulders. Gently sloped, slow-moving streams may only be able to transport grains of sand and smaller particles. The velocity of water flowing across the broad landscape also affects the size of sediment this water can transport, but the size range of materials that can be transported is much smaller. Stationary, ponded water has no energy to hold particles except for the finest suspended clay particles. Thus the sizes of sediment that you observe have been moved by flowing water indicate the velocity/power of water flows that have occurred there and the sizes of sediment available to be moved—primarily during the last flood and perhaps during the preceding flood.

Principle: Observe the size and location of naturally deposited sediment in order to select, place, and size appropriate water harvesting and erosion control structures

If you observe boulder-strewn drainages, this indicates potentially intense water flows occur there. In almost all cases, stay out of boulder-strewn drainages. Instead, focus water harvesting and erosion control efforts on more gentle slopes in the broad landscape and in contributing smaller drainages.

When building the rock structures that are described later in this chapter, the rock size should be larger than about 90% of the naturally deposited rock you currently see in the channel. This will reduce the chance that the structure and its rock are "blown out" in a big flow.

Different materials are better suited for capturing different sizes of sediment. Rock structures can capture "bed load" particles such as sand and larger materials that roll, slide, and hop along the bed or bottom of the waterway. Finer clay and humus particles—the ones that are best for holding onto soil moisture—are called "wash load" particles. These are held in near-permanent suspension in flowing water and only settle out in pooled water or on the floodplain where flow ceases. When flow resumes, the fine sediment particles move on unless vegetation has grown up through the muddy fines to bind them in place. Vegetation can capture fine wash load particles because vegetation can grow to be much more dense and

effective at slowing water flow than rock structures. In addition, positively charged plants such as sedges attract the negatively charged clay and humus particles and hold them in place.

Unlike upland vegetation that is adapted to drier conditions, wetland vegetation can move oxygen down to its roots. So even when wetland vegetation is covered in anaerobic mud lacking oxygen, it can easily grow through the mud, binding it in place with its roots.

PATTERN AND PRINCIPLE THREE
Guiding In-channel Strategies

Pattern: Steep waterways naturally form stepped pools that dissipate energy

In general, sections of streams with a slope steeper than 4% dissipate energy vertically through stepped pools as opposed to dissipating energy laterally through meandering. Meandering stepped pools dissipate energy both ways.

Principle: Mimic what works in nature

In eroding channels with a slope steeper than 4%, consider stabilization strategies that incorporate stepped pools (figs. 10.8A and B, 10.9).

Fig. 10.8A. Large meadow-draining headcuts on Placer Creek, Carson National Forest, New Mexico, 2013. Unless stopped, headcut erosion continues moving upstream. Credit: Craig Sponholtz

Fig. 10.8B. Headcuts stabilized and meadow rehydrated using a large log and rock stepdown structure that creates meandering stepped pools, 2016. Designed and built by Craig Sponholtz of Watershed Artisans, Inc.

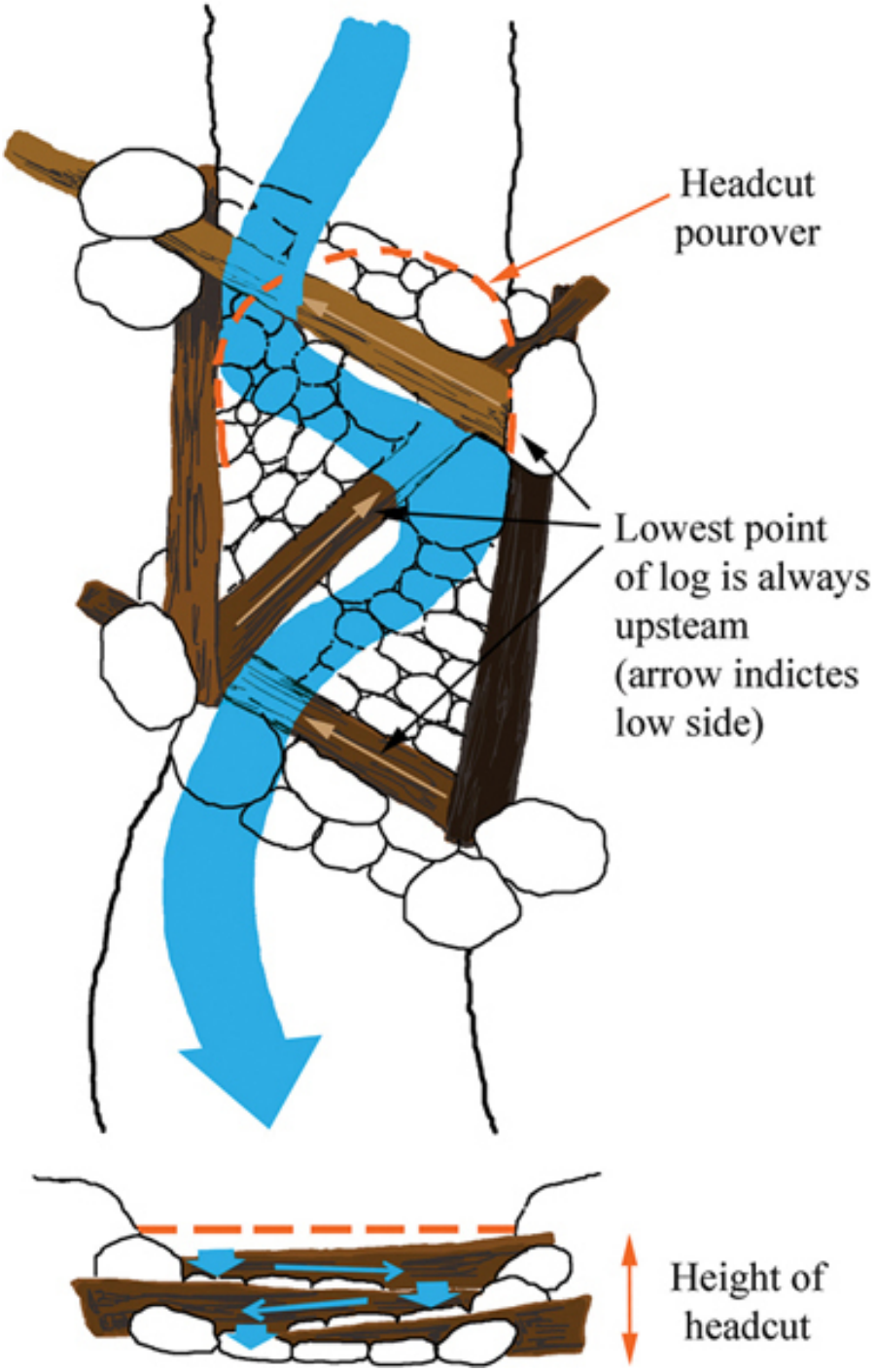


Fig. 10.9. Log and rock stepdown, or stepped pools. Logs should be oriented so that the lowest point of the log is always on the upstream side of water flow (arrow indicates low side). Adapted from design by Craig Sponholtz

PATTERN AND PRINCIPLE FOUR
Guiding In-channel Strategies

Pattern: Gradually sloped waterways typically have meandering flows

In waterways with less than a 4% slope, and more typically with less than a 2% slope, the energy of the flowing water tends to be diffused by meandering flow patterns (fig. 10.10). The more the waterway meanders, the greater the distance water must flow to get from the top of the waterway to the bottom. This reduces the gradient or slope of the bed of the waterway, which reduces the erosive speed of the flow while increasing the duration of the flow. The water comes into contact with more of the surface area of the channel bed, allowing more water to infiltrate subsurface to recharge wells, springs, and aquifers, and to provide moisture for more plants along the waterway. Outer bank erosion (fig. 10.10) exposes courser horizontal lenses of soil (like sand, gravel, and cobble) into which water readily infiltrates and saturates before reentering the creek further downstream—resulting in a natural sub-irrigation system sometimes valley-wide that also cools water temperatures improving habitat for trout, salmon, and other life.

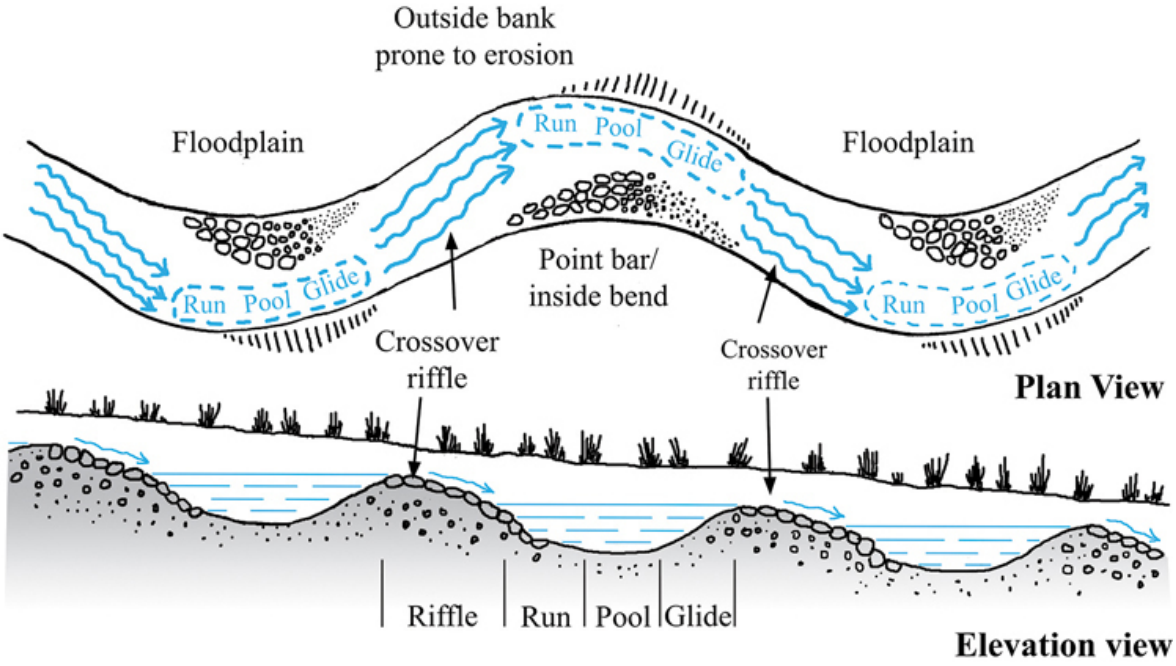


Fig. 10.10. Patterns within a healthy meandering waterway. Crossover riffles are the reaches of a channel where water flow crosses over (at a relatively even depth) from one meander bend and its pool to the next meander bend and pool. Note: the vertical scale is somewhat exaggerated in the elevation view above to more easily show the patterns of change in elevations. Adapted from *Let The Water Do The Work* and *Erosion Control Field Guide*

Conversely, when a channel is straightened and steepened, the velocity increases and the erosive force of the same volume of water increases. As you double

grade/steepness of a waterway, you increase the volume of sediment it can move by *four times*, and increase the size of the particles it can move by *eight times*.[3] This dramatically increases the potential for erosion. Water flowing fast in a straightened and steepened channel takes up much less space—perhaps just half the width—than the same volume of water flowing in an unstraightened and unsteepened channel. Try walking across a steep, straight channel and you'll see how difficult it is due to the force of the flowing water.

Principle: Mimic what works in nature

Meandering is good. Let it happen where practical. It is a natural process in which the erosive force of water flow in an incised waterway is dissipated as the flow cuts into alternate banks of the channel, inducing the redistribution of bed materials and the gradual evolution to a wider waterway with a longer flow path and a more gradual slope. In the course of this natural process, constricted channels "heal" themselves over time by creating a widened, healthy floodplain.

PATTERN AND PRINCIPLE FIVE
Guiding In-channel Strategies

Pattern: The riffle–run–pool–glide dissipates energy, recharges groundwater, and lengthens life's access to surface water

The terms *riffle*, *run*, *pool*, and *glide* refer to the characteristics of both the channel bed and the water flowing over it (fig. 10.10). *Crossover riffles* are the locations of a meandering channel where water flow crosses over from one meander bend and pool to the next meander bend and pool (fig. 10.10). The steepness of the channel and speed of water increases as water flows cross over and down riffles. This high-energy water carries away finer-grained materials, leaving only heavier materials behind in the riffles. The roughness of that heavy material can somewhat dissipate the energy of the water flowing over it.

Hydrologist and geomorphologist Dave Rosgen says "The river gets off the mountain on the riffles." I experienced this when I rafted down the Colorado River through the Grand Canyon. Most of the meandering trip was slow and gentle, but it was peppered with excitement when the speed and roughness increased as we went over and down steeper riffles— the locations where you really see and feel the river dropping in elevation as you move downstream.

The *run* (fig. 10.10) is the steepest section, transporting sediment and preventing deposition. At the bottom of runs, *pools* (fig. 10.10) are created. The pooled water helps dissipate the force of incoming water. Pools are deepest on the outer bend of

the meandering channel where water moves somewhat faster and where more sediment is removed. Pools are shallowest on the inner bend where water moves slower and sediment can deposit. Pools provide a diversity of habitat for aquatic life, enhance recharge of groundwater, and can lengthen access to surface water when intermittent flows of the waterway cease.

As water leaves the pool, it *glides* (fig 10.10) upwards toward the next riffle. The pools are self-scouring and self-maintaining since much of the sediment scoured from the run and pool is dropped along the glide and at the top of the next crossover riffle. Flowing water is at its most shallow at the top of the glide and the upstream side of crossover riffles (the crest). As a result, water looses energy and sediment naturally deposits here. Crossover riffles can be ideal locations for the one-rock dams described later in this chapter.

In meandering intermittent and ephemeral waterways that are located in sediment-rich drylands, pools often "disappear" when water flow lessens and stops. This happens because standing or slow-moving water can no longer carry the abundant fine sediment within it, so the sediment settles out and fills in the pools and may bury the riffles. However, this sediment can be scoured out again in the next water flow. This is particularly evident in sand bed streams (see the dashed *fill line* in fig. 10.28).

Principle: Look for, and work with, the riffle–run– pool–glide pattern

When you are planning to work in an unhealthy, eroding channel, look for a nearby healthy "reference channel" or "reference reach" to model your work on. This should be a long stretch of healthy channel with multiple meanders in a similarly sized watershed with similar slope that has a healthy riffle–run–pool–glide pattern and healthy spacing.

Place sediment-trapping structures like one-rock dams (ORDs) (described later in the chapter) in locations where sediment naturally collects, such as at the top of a glide and the crest of a crossover riffle. Do not place ORDs in locations where sediment will be scoured out, such as within a pool.

When you have an increase in channel steepness (a riffle), which may be natural or may be due to a disturbance or to your work, expect and plan for the resulting run–pool–glide pattern that will follow.

Note that, at the inside bend of a point bar (fig. 10.10) you typically find larger rocks on the upstream side and fines on the downstream end. Bill Zeedyk minimized destruction and work of those mining sand throughout a creek, by recommending they only take sand from downstream ends of the point bars, while

leaving the rock in place at their upstream sides. As a result, the point bars remain and sand naturally redeposits on the downstream ends by the water flow.

PATTERN AND PRINCIPLE SIX
Guiding In-Channel Strategies

Pattern: Water flows perpendicular to what it flows over

Water flows perpendicular to what it flows over, and bends in the direction of the steepest downhill path (Fig. 10.11). Get out into a natural creek or river and watch this pattern in action. Observe what happens as water flows over rock, branches, and other material sitting at different angles to the water's flow. How does the water flow just below that material? Faster? Slower? Has a pool formed, or is there sediment deposition? Learn from these natural flows, keeping in mind that if you build similar forms, they will similarly affect the flow. All actions cause reactions.

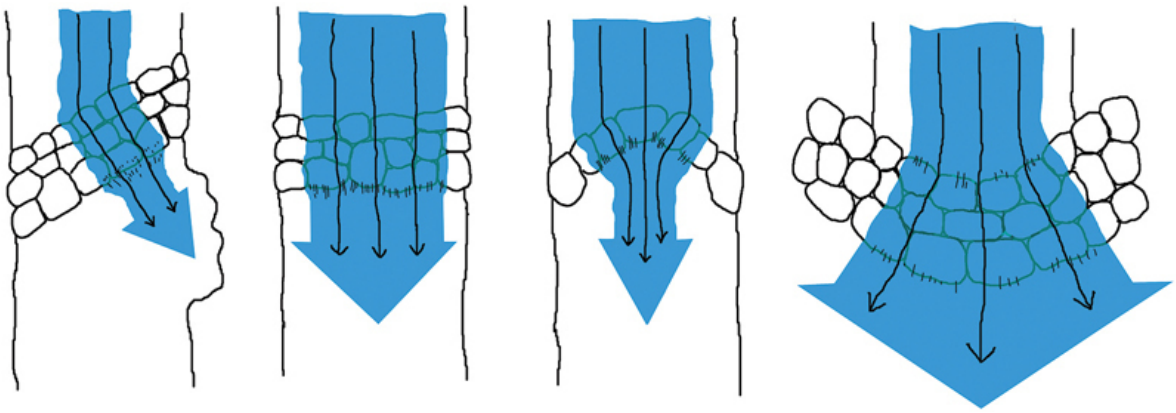


Fig. 10.11. Water flows perpendicular to what it flows over, and bends in the direction of the steepest downhill path

Principle: Always consider how your actions will affect the flow

In the strategies section of this chapter, you'll see how different strategies affect the flow of water. Depending on the angle you build structures at in relation to the flow path of water in the channel, you can focus water flow toward the center of the channel, spread it out more broadly, or even direct it into the bank to induce more of a meander. Your selection of strategies, and their placement relative to water flow, will depend on what the stream needs to repair damage and improve stream health.

PATTERN AND PRINCIPLE SEVEN
Guiding In-channel Strategies

Pattern: The speed, depth, and volume of water flow determines what the water can carry

Decreasing the speed, depth, and/or volume of flowing water *decreases* the flow's ability to carry sediment. *Increasing* the speed, depth, and/or volume of flowing water *increases* the flow's ability to carry sediment. See the Tracking Water and Sediment Flow section of chapter 1 for more information.

Principle: Consider *decreasing* the speed, depth, and/or volume of flowing water where you want to capture sediment

Examples of locations where you might want to capture more sediment include eroding areas where you want to stabilize soil loss and where you want to regenerate living sponges of healthy soil and vegetation. To accomplish this, use the sheet flow collector, one-rock dam, filter dam, and especially the sheet flow spreader strategies described later in this chapter.

Principle: Consider *increasing* the speed, depth, and/or volume of flowing water where you need to move sediment

Examples of areas where sediment needs to be moved include locations that are prone to clogging because they decrease a flow's ability to carry sediment such as a curb cut inlet (fig. 10.12) or a culvert inlet that needs a drop inlet (fig. 9.2). But be careful when you increase the force of flowing water. Because the potential for unwanted erosion greatly increases, such interventions must be very well built and stable.

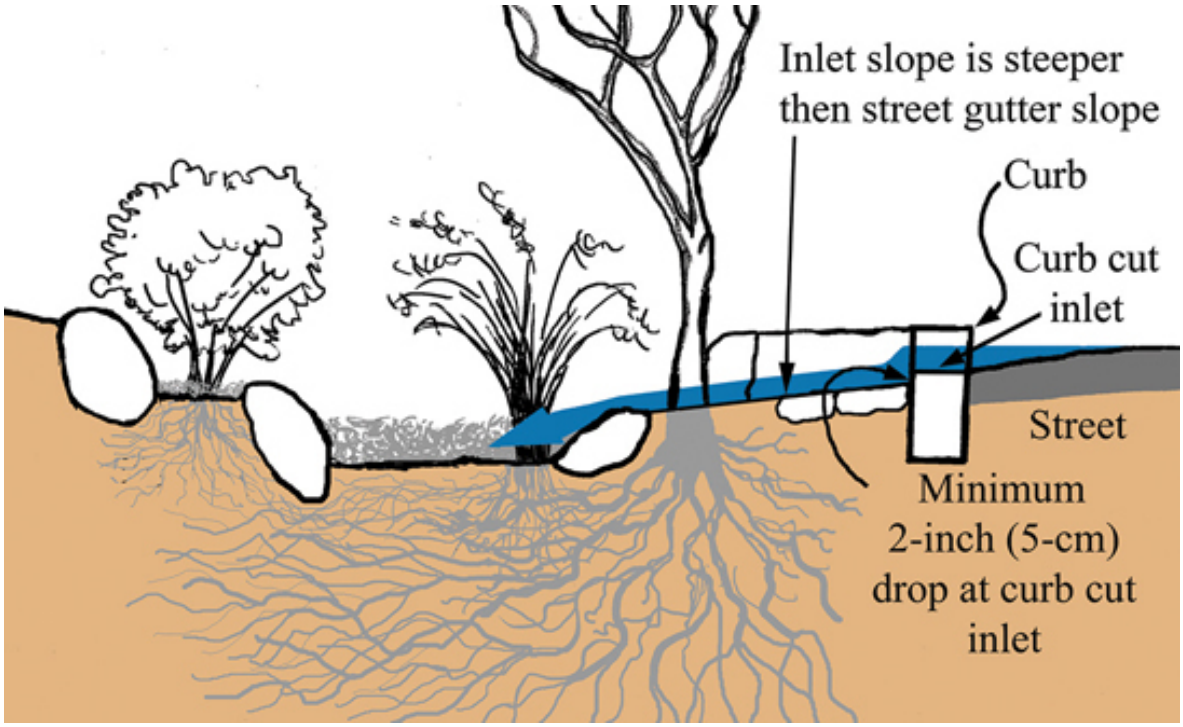


Fig. 10.12. Water flowing down a street gutter can be directed to a street-side tree basin via a curb cut or curb core inlet (see chapter 8 for details). While these inlets beneficially divert street runoff to adjacent plantings, they are prone to clogging with sediment since the flow slows down as it turns 90° to enter the inlet. Water flowing into a curb core hole can also be slowed down because the inlet is narrower than the street gutter. Constructing a mini-waterfall-like drop at the inlet, and/or sloping the curb core hole and the inlet slope at a steeper angle than the street gutter, increases the speed of flowing water and reduces clogging at the inlet. This increases the ability to carry, rather than deposit, sediment. The inlet slope can be armored with rock if needed, but the tops of all rocks must be at least 2 inches (5 cm) below the bottom of the inlet.

PATTERN AND PRINCIPLE EIGHT
Guiding In-channel Strategies

Pattern: Everything in a stream is striving to find its angle of repose

The angle of repose is the angle or steepness at which unconsolidated material can remain stable. And there is no end to that unconsolidated material because sediment is constantly moving down through the system with the water's flow like a conveyor belt; continually replenished by the sediment in the runoff flowing into the channel.

Principle: Be sure to make transitions more gradual and longer if your in-stream work has significantly lifted the grade or created a drop off in relation to

the existing stream gradient and conditions. Building a series of one-rock dams (ORDs) (see one-rock dam section) of equal height throughout a channel's reach makes for a more gradual transition, while the opposite occurs when building a series of ORDs of different heights throughout that reach or when building a single ORD in the channel. To repair a steep head-cut, a more gradual transition can be created with a more gradually sloped rock-mulch rundown, sheet flow collector, and/or Zuni bowl (all described in the next section. This is in contrast to attempting such a repair using a gabion or check dam having a pour over (the location where water flows or pours over the structure) that is as steep as the original headcut.

PATTERN AND PRINCIPLE NINE
Guiding In-channel Strategies

Pattern: New structures are stronger after being filled in with sediment and vegetation

New structures need to be filled in with sediment and vegetation in order to reach their maximum strength and stability since they are weakest before water flows have deposited sediment in and around them. Ideally, one or more small, gentle storms will deposit the initial sediment and germinate seeds that grow anchoring roots. This will make the structure stronger and more able to withstand a big storm with its more forceful runoff.

Principle: Seed structures during their construction to jumpstart revegetation. When using rock, lay rocks tightly together and backfill structure with smaller aggregate if available.

This will reduce erosive piping—water rushing through pipe-like holes between the rocks—and help catch more fine-grained particles. Additionally, after constructing the mass of your structure, place progressively smaller aggregate from small-sized rock to gravel to soil as you move upstream. This mimics the deposition that would occur naturally in smaller flows (the filter dam in the next section is a great example of this). Such pre-filling of the structures reduces maintenance needs down the road and enhances revegetation.

Moisture can condense on rock and gravel on cold mornings when the rock and gravel is colder than the warming air temperature, and seep into soil rich in organic matter to help sprout seeds and irrigate seedlings.

To capture even more moisture in an ephemeral or intermittent waterway, during construction of a one-rock dam add a layer of soil on top of the gravel belt

on the structures' upstream side. This will help create a water-retaining depression just upstream of the structure during the next flow.

STRATEGIES INFORMED BY NATURAL PATTERNS AND PRINCIPLES

When working in or assessing a waterway, ask yourself, "What part of the channel am I in now, what are the characteristics of its flow, and what are the effects of this flow?" (See fig. 10.13). If the system is degrading and an intervention is needed, ask yourself, "What characteristic of flow is needed here and what type of intervention would create that characteristic?"

The strategies described below are generally presented in order of their placement from the top of the watershed down to the bottom, as shown in fig. 10.13.

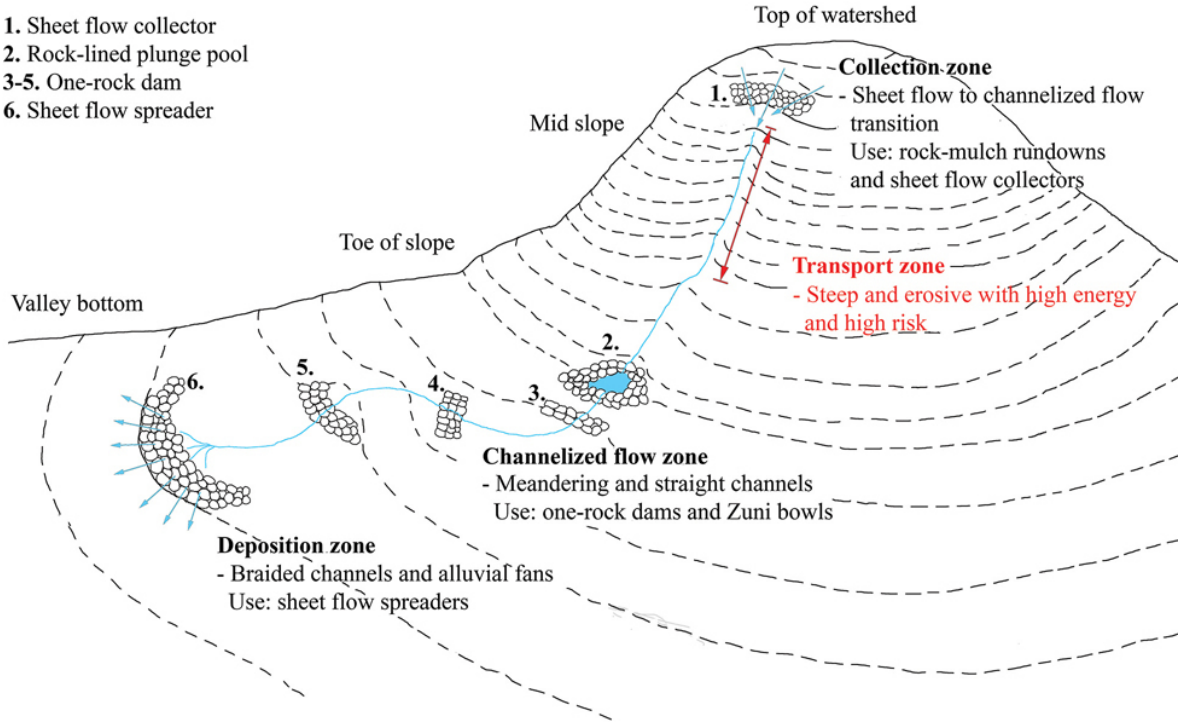

1. Sheet flow collector
2. Rock-lined plunge pool
3-5. One-rock dam
6. Sheet flow spreader
Top of watershed
Collection zone
- Sheet flow to channelized flow transition
Use: rock-mulch rundowns and sheet flow collectors
Mid slope
Toe of slope
Transport zone
- Steep and erosive with high energy and high risk
Valley bottom
Channelized flow zone
- Meandering and straight channels
Use: one-rock dams and Zuni bowls
Deposition zone
- Braided channels and alluvial fans
Use: sheet flow spreaders

Fig.10.13: Placement of in-channel strategies based on landform. Adapted from *Erosion Control Field Guide* by Craig Sponholtz and Avery Anderson

These are a few of your options; see appendix 4 for more resources on how to "read" water and sediment flow and additional options. All of these strategies can be constructed using simple hand tools such as shovels. They can also be up-scaled and constructed using machinery. Experiment with handwork first to learn at that scale before up-scaling to machines. Whatever the scale, the better you collaborate

with natural patterns and flows the better your craft and work quality will be, and the better the structure will look and perform (fig. 10.14).

Fig. 10.14. Using hose water, Bill Zeedyk created this "play creek" during a workshop to illustrate flow patterns and to try out strategies to see their effects on multiple scales. Near the top, headcut erosion has formed at a steep drop. A pebble Zuni bowl (or rock-lined plunge pool) mitigates a similar headcut below.

A one-rock dam (ORD) in the foreground further stabilizes the Zuni bowl by backing up a pool of water to its spillway.

KEY QUESTIONS ABOUT STRUCTURES IN THIS CHAPTER

Why are almost all the rock structures in this chapter only one rock high?

- Vegetation is regenerative, helps hold rock in place, and when combined with r creates more resilient systems. With only one vertical course of rock, seed is mu more likely to germinate between the rock, growing plants that help anchor the rock and form the living elements of the structure.
- One-rock high structures are more structurally sound than taller rock structures to the nesting of each rock to soil.
- Limiting the height of structures reduces the force of the water flowing off their downstream side, which reduces potential erosion (see patterns and principles FOUR and EIGHT).
- Limiting the structure to one vertical course of rock encourages careful construction, which leads to greater effectiveness and beauty.
- This approach minimizes the amount and cost of transported material.

Why aren't this chapter's structures wrapped in wire fencing like a gabion, or plastic netting like an erosion control straw-stuffed wattle?

- Unwired, unnetted structures are more natural. If they fail, all you'll see are som naturally scattered rocks or brush.
- In contrast:

- A failed gabion (a structure of rock wrapped in a basket or "burrito" of wire fencing) leaves shards of sharp, bent, rusting metal fencing.
- Straw wattles (a sausage or snake-like structure of straw that is stuffed into a tube of plastic netting) traps and kills wildlife such as lizards and snakes and often washes away to form piles of litter.
- Sand, gravel, and cobble within the water flow will abrade the galvanized coating of a gabion's wire, speeding up its deterioration from rust. Plastic netting will deteriorate in the sun's ultraviolet light.
- Due to their failure rate, gabions and wattles are often referred to as "time

release sediment capsules" because the question is not *if* they will fail, but *when* they will fail and release all the sediment they were holding back.

- The wire or wattle netting is perceived to be the structural element so the rock c straw fill is often applied in a weak, sloppy manner leading to greater failure and ugliness.
- Wire-wrapped or netted structures are typically built too high, greatly increasin chance of failure. There is more water pressure on their upstream side and they create steep waterfall-like spillways on their downstream side, increasing the potential for scouring erosion.
- Wire structures tend to be squared off on every edge so it's difficult to achieve naturalistic forms.
- You have to buy and import the wire fencing or netting.

How can you get more height and strength from a one-rock high structure?
See fig. 10.15

Fig. 10.15. Rock is laid on its narrow side (bookended) rather than its wide bottom, so the height of the one-rock high structure is created by the greater width of the rock. Larger "footer" rocks are placed on the downstream

(foreground) side to help anchor smaller, lighter rocks on the upstream side. Rockwork is further stabilized and strengthened by 1). Laying most rocks lengthwise, parallel with the water's flow, 2). When feasible, anchoring or keying rockwork into bedrock or large boulders, 3). Maximizing each rock's surface contact with each adjacent rock allowing no unnecessary gaps or spaces, 4). Setting rocks to create a relatively even (not jagged) form to the structure so it won't channelize and constrict flow, 5). Rocks are alternated (as you would lay brick) so there are no continuous joint lines (water routes) between the rocks, and 6). After laying the rock, do the "kid test" (jump and play all over the rocks like a kid) to ensure all rocks are secure. If any rock moves, reset it so it does not move, since water can move anything a kid can move. Work by Craig Sponholtz of Watershed Artisans, Rio Mora National Wildlife Refuge, New Mexico

TOOLS

- Basic hand tools used to construct these strategies include shovels, digging bars pry bars, pick-axes, wheelbarrows, rock litters (figs. 10.16 and 10.17), and rock rakes.

Fig. 10.16. Useful tools and materials for rockwork. Wheelbarrow retrofitted with a second set of handles so it can be carried over rougher terrain. Credit: Craig Sponholtz

Fig. 10.17. Rock litter used by Steve Carson and Lincoln Perino

- To check relative elevations, measure slopes, and determine level surfaces, leveli tools such as a bunyip water level, A-frame level, carpenter's level, laser level (se appendix 1), or string level (box 1.2) can be used.
- Constructing brush structures will require pruning saws, pruning shears, post-h diggers, and perhaps a sledgehammer to drive wooden stakes into the ground.
- You will also need protective clothing, gloves, and boots.
- For larger-scale projects a backhoe with thumb (an attachment that holds mate in the claw of the backhoe) can dig anchoring trenches and transport and set ro

MATERIALS

- **Rock type**. Use naturally angular rocks, which have angled edges that easily loc into one another, making this a better choice than round rock. This will also giv your structures a natural appearance. Avoid unnaturally angular rocks such as b rocks that have been mined/dynamited, which have an unnatural appearance ar are more difficult to work with (unfortunately blast rock is all too common in t landscape materials industry). See equation 18 in appendix 2 to estimate neede rock volume.
- **Rock size**. The size of rock you use should be larger than about 90% of the typ naturally deposited rock you currently see in the channel in order to reduce the chance of the structure being blown out in a big flow. But don't use greatly over rock—this will cause excessive turbulence that could undermine the structure.[4] you are building a rock structure in a sand channel that has no naturally deposi rock, you may want to import and use rock with an average size that measures approximately 1/8th of the total channel width. For example, in a 6-foot (200-c wide channel, 8- to 10-inch (20- to 25-cm) rock would be used to construct a c rock dam across the channel width.
- **Where to collect rock**. To minimize land disturbance and soil erosion, collect r that is laying on the surface rather than digging out partially buried rock. Take from more stable gradual slopes or flat areas located upslope of where you plan build a structure. A structure constructed just below the area of rock-collecting disturbance will catch eroding soil and keep it in the landscape. If there is life growing on the rock such as moss or lichens, place that growing area toward the light rather than the soil, so it will keep on living and looking great.
- **Salvaged chunks of concrete**. Salvaged materials can be used in place of rock. Concrete is a durable material readily available in the urban environment, often found in 4-inch (10-cm) thick pieces of broken sidewalk. Laid skillfully, salvage concrete looks great. A 404 permit will not allow its use if it has metal in it.
- **Seed**. Ideally, use a diverse mix of perennial and annual grasses that are native to area and to the site's microclimate, and that are able to grow up through accumulating sediment.
- **Brush, branches, and pole cuttings**. All woody material has limited longevity, its use will depend on the application needed. Ask yourself how long the structu needs to last before the area will become naturally stabilized, then select the placement, structure, and type of material accordingly.

- For greater structural integrity, use green wood freshly cut from live plants, or carefully prune or coppice appropriate plants to obtain living material.
- Where material is sparse, you can more sustainably obtain it by carefully pruning lower branches from nearby trees (see chapter 11 for pruning tips).
- Poles cut from native willow, cottonwood, and aspen work well in areas where these trees are commonly available. These trees readily recover from pruning or coppicing.
- Seep willow (*Baccharis salicifolia*) can be used in drier areas of the U.S. southwest.
- Fresh cuttings from poplar, cottonwood, and willow can grow into new plants if the freshly cut end is placed deep into moist soil, speeding vegetation growth and enhancing the drainage. Best done in plants' dormant season.
- Avoid using invasive non-native plants such as tamarisk (*Tamarix ramosissima*) in the U.S. If they are present and are already dead or being removed they can be used, but let the cut wood mature or air dry first to ensure it can't root if placed in moist soil.
- Rot/decomposition of the wood is quicker when used in locations alternating between wet and dry. In contrast, keeping the wood constantly wet in perennially anaerobic conditions can greatly diminish the rate of decomposition. The type of wood will also affect its durability. Hardwoods tend to last longer than softwoods, as do rot-resistant woods such as juniper and cypress.

PERMITS, PERMISSIONS, AND POTENTIAL FUNDING

Whether on private or public land, stream restoration projects may require some form of federal, tribal, state, or local permitting to ensure the project is in compliance with the U.S. Clean Water Act (CWA) and other regulations. Before you begin, obtain permits and research requirements by contacting the U.S. Army Corps of Engineers (USACE), the U.S. Environmental Protection Agency, and the applicable tribal, state, and local departments of environmental quality in your area. The CWA's section 404 permits through the USACE are the most common requirements, along with section 401 state certifications, which are required for 404 permits.

Obtaining and adhering to permits is important to ensure work is conducted correctly without negatively impacting the environment. Environmental departments may require the permit holder to collect and report environmental quality data from the project site. This monitoring is valuable because it gives you and them data on the effectiveness of the project strategies over time. Environment staff and applicants can also beneficially share ideas regarding design and construction methods to enhance and protect our common waters.

For permitted projects, grants may be available from the U.S. Environmental Protection Agency and other federal agencies, tribal governments, state agencies, private foundations, and nonprofit organizations.

TAKE *BEFORE* PHOTOGRAPHS NOW; TAKE *AFTER* PHOTOS FOR YEARS

To monitor the effectiveness of your work, photograph conditions before you start work, just after completion, and over the seasons and years ahead. Take repeat photos the same time of day so light angles and shadows are similar. It is useful to take photos in both wet and dry seasons, year after year, on the same dates each year, if possible. It is also useful to get copies of historic photos of the site if they exist.

Establish permanent photo monitoring points from which to take pictures. Position photo monitoring points so they focus on areas where you expect to see the greatest change over time. Photograph both upstream and downstream views. Place photo monitoring points where they will be easy to find and will not become overgrown by vegetation or erode away. Try to include reference points that will endure over time in the frame of the photos, such as hills, mountains, large rock outcroppings, buildings, or large trees. Include the horizon in your photos when possible. Take photos from the same height above the ground—such as atop a stake or tripod or at eye level when standing.

Photo points can be marked with a pile of rocks, a rebar stake, or a t-post on which you can set the camera to take pictures. Number each photo monitoring point and label it with a metal tag. Record the GPS location, the photo point number, and the compass direction you point the camera in. Ensure all your photos are filed with their date and exact photo point location.

BE SAFE

Do not throw rocks! Look around to make sure everything and everyone is clear before swinging a tool or moving a machine. Work carefully. Do good quality, while keeping all fingers, toes, limbs, bodies, and heads healthy and safe.

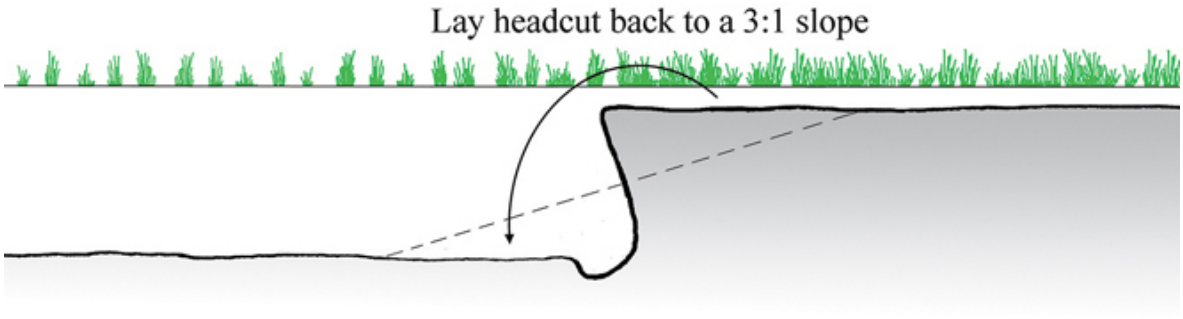
Strategy: ROCK-MULCH RUNDOWN

Step one, review these Patterns and their Principles at beginning of chapter
1. The health of a waterway is as strong as its connection to its floodplains
2. Sediment size and distribution are "tracks" of the flow
7. The speed, depth, and volume of water flow determines what the water can carry
8. Everything in a stream is striving to find its angle of repose
9. New structures are stronger after being filled in with sediment and vegetation

A rock-mulch rundown is an erosion-controlling layer of rock mulch, one-rock thick, which is used to armor a steeper-sloped, low-energy, water-flow location. Its primary purpose is not to harvest water, but to direct flowing water to a less potentially erosive location where water can be harvested and infiltrated more easily and effectively. The rock-mulch rundown works great to direct water from a downspout outlet into a water-harvesting earthwork (fig. 2.18B). It can also armor an overflow spillway that conveys water over a steep slope from one water-harvesting earthwork to another.

A rock-mulch rundown can be used to control headcut erosion, but ONLY on low-energy headcuts, such as headcuts with small catchment areas located at the top of upland rills and gullies where calm sheet-flow concentrates into more destructive channelized flow (fig. 10.18). To construct the rock-mulch rundown, dig the erosive vertical face of the headcut back to a stable angle of repose (no steeper than a 3:1, 18˚, 33% slope), minimizing disturbance of existing vegetation (fig. 10.19A).

Fig. 10.18. Rock-mulch rundown at top of photo, stabilizing a once erosive head cut. The center of the structure is lower than the sides to ensure water flows down—not around—the structure. A rock-mulch rundown/one-rock dam hybrid is installed at the next steep section below. Designed and built by Craig Sponholtz. Rio Mora National Wildlife Refuge, New Mexico



10.19A. Side or elevation view of a headcut where sheet flow becomes channelized flow. Dotted line represents the more gradual slope to which the headcut needs to be dug back, filled, and compacted before rock-mulch rundown is constructed.

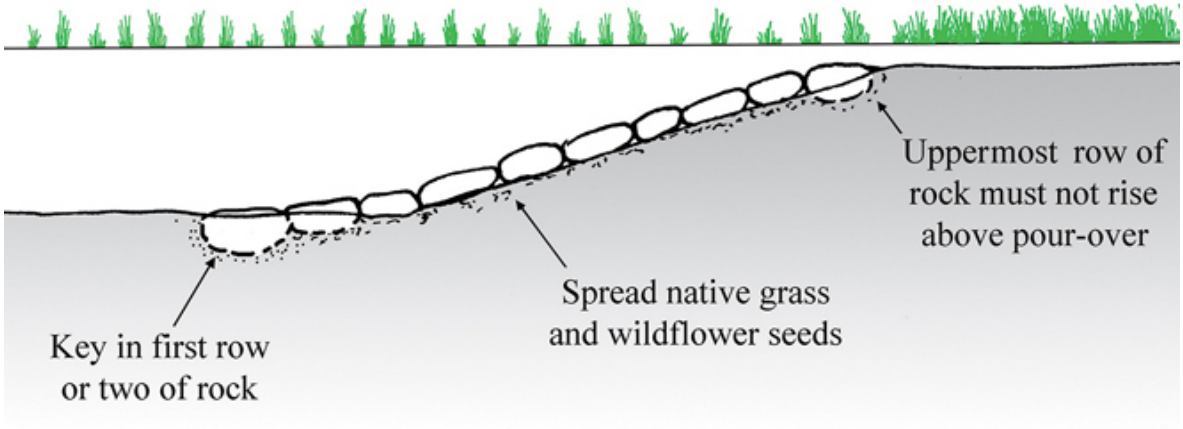

Uppermost row of rock must not rise above pour-over
Spread native grass and wildflower seeds
Key in first row or two of rock

Fig. 10.19B. Side or elevation view of a rock-mulch rundown. To anchor the structure, use the structure's largest rocks to key-in the first downslope row or two as a footer. Ensure the downslope edge of the top of the rock is level with the bed of the channel to avoid creating an erosive waterfall-like drop. Just before laying the rest of the rock one course high, broadcast native grass seed over the section of the slope you'll lay rock on to speed the growth of anchoring vegetation between the rock. In high clay soil, consider applying a granular filter before you lay the seed and rock (box 10.2). The uppermost row of rock must not rise above the headcut pour-over location, as this would cause water to flow around— rather than down—the structure. Lay all rock tightly together and fill any gaps with smaller rock and gravel. Adapted from *Erosion Control Field Guide* by Craig Sponholtz and Avery C. Anderson, Quivira Coalition, 2012

Narrow headcuts may need to be widened to accommodate rock work.[5] Compact the soil, then cover the slope with a single layer of tightly fitted rock mulch (fig. 10.18, 10.19B). The rundown *must be lower in the center than on either side* to ensure that water flows down the center of the structure as opposed to

erosively flowing around it. Since there is no mortar in the structure and it is only one rock high, water can infiltrate between the tightly fitted rocks and sustain the growth of vegetation that helps stabilize the structure and slow water flow. Do NOT use a rock-mulch rundown within channels that have moderate- to high-energy flows, such as channels below headcuts. In those instances, investigate whether one-rock dams or rock-lined plunge pools are appropriate for the site.[6]

Box 10.2. Granular Filter Option in Clay Soils

According to Craig Sponholtz, in channels with high clay soil it is wise to build the entire ramped section of your rock-mulch rundown atop a granular filter. This granular filter should be made up of a 3 to 6-inch (8 to 16-cm) layer of unwashed gravel with a 3-inch (8-cm) minus particle size so your rock does not sink and disappear into wet, oozy clay (see fig.10.31 in the filter dam section). The fine particles in the unwashed gravel will give your seeds something to germinate in.

Lay down the gravel filter, then the seed, then bed (set) the rock into the gravel. If you can't get gravel, a natural coarse fabric is your next option, such as coarse burlap, jute mesh, or coir/coconut mesh. Gravel is superior to fabric, since the gravel will get fully incorporated into the wet clay soils and begin to change its characteristics to be more structurally sound. Do not use synthetic fabrics because they are too smooth, won't incorporate into the soil, and will act as unstable "slip and slides."[7]

Create with your site's unique potential

Figures 10.20A to 10.20D illustrate a wonderful example of a rock-mulch rundown hybridized with other strategies described in this chapter to maximize its effectiveness. Don't be rigid. Let the unique landforms, challenges, and potential on your site inform your work and spark your creativity.

Fig. 10.20A. Water flow is diverted off a dirt road via a rolling-dip diversion swale (details in chapter 9), then spills over a steep slope via a rock-mulch rundown. Designed and built by Craig Sponholtz at Plants of the Southwest Nursery, Santa Fe, New Mexico

Fig. 10.20B. A hybrid structure consisting of a rock-mulch rundown at the top, a rock-lined plunge pool in the middle to provide more water to the structure's plantings, and a sheet flow spreader at the bottom. Rock is placed around new plantings that were hand watered until the rains began a couple of weeks later. Arrows denote water flow.

Fig. 10.20C. Structure during a runoff event

Fig. 10.20D. Structure one year after installation. Note the abundant native grass growing in the alluvial fan of sediment and runoff at the base of the structure.

Strategy: SHEET FLOW COLLECTOR

Step one, review these Patterns and their Principles at beginning of chapter
1. The health of a waterway is as strong as its connection to its floodplains
2. Sediment size and distribution are "tracks" of the flow
6. Water flows perpendicular to what it flows over
7. The speed, depth, and volume of water flow determines what the water can carry
8. Everything in a stream is striving to find its angle of repose
9. New structures are stronger after being filled in with sediment and vegetation

A sheet flow collector, also called an *ends down media luna* (crescent moon), is similar to a rock-mulch rundown in that it also stabilizes eroding slopes where spread out sheet flow is transitioning into more concentrated channelized flow.

However, a sheet flow collector is wider—slowing, spreading, and sinking more of the flow along the entire width of the eroding transition zone.

To construct a sheet flow collector, each row of rock is laid level on the land contour, so the landform determines its shape. As with a rock-mulch rundown, you may first need to lay headcuts back to a more gradual angle of repose before constructing the sheet flow collector (fig. 10.21A). Position the downslope edge/row of rock by using leveling tools (appendix 1) to find a level line arcing across the slope and its narrowing channel. Point the ends of the structure upslope to help focus water flow over and through the structure, preventing water from cutting around the ends (fig. 10.21B).

Fig. 10.21A. A wide transitional headcut formed as sheet flow was concentrated at the top of a gully network at Arroyo San Pablo, New Mexico. Credit: Craig Sponholtz

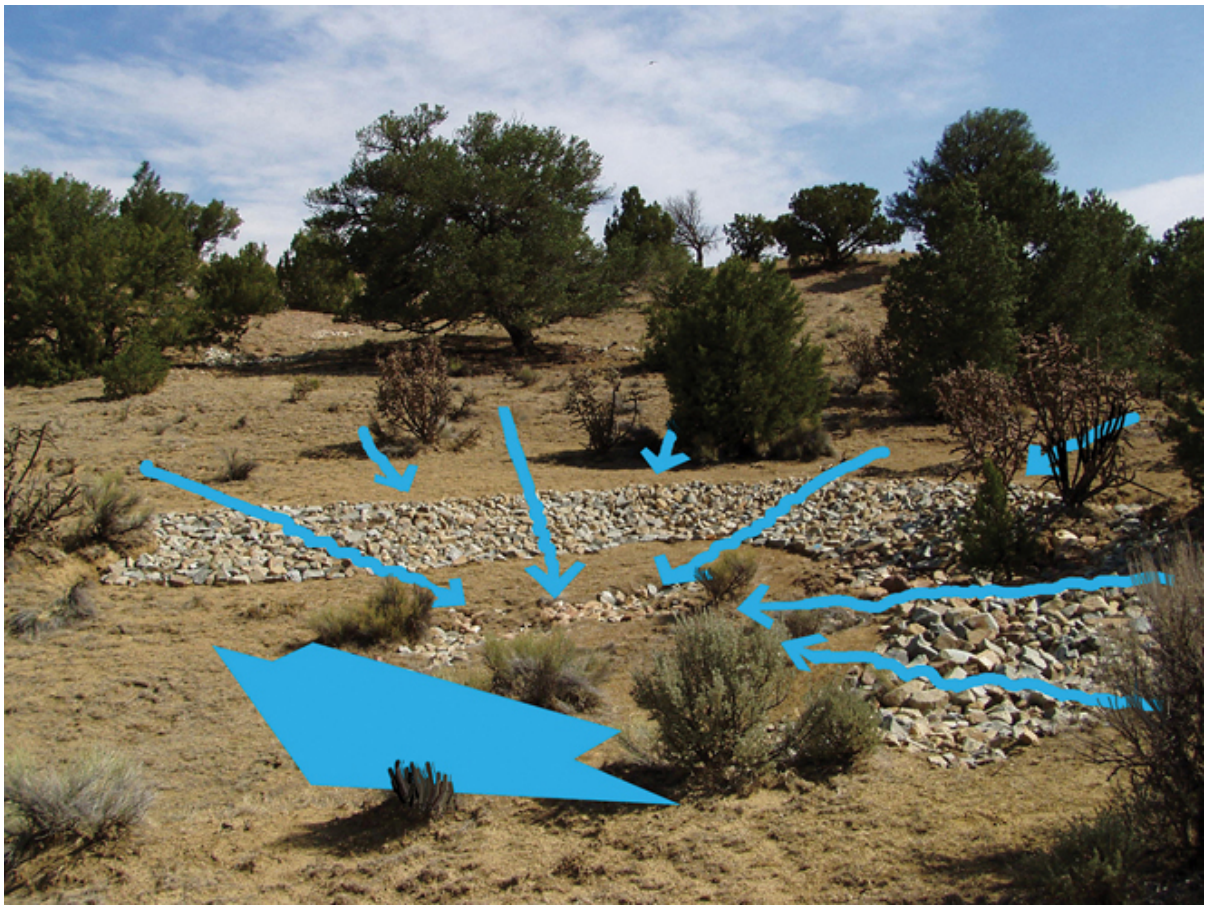


Fig. 10.21B. The headcut was laid back with hand tools, seeded, and covered with a sheet flow collector of hand-placed rock in a collaborative project with the Cuba YCC, Rio Puerco Management Committee, and Watershed Artisans. Credit: Craig Sponholtz

Fig. 10.21C. Two years later, the headcut is stabilized and supporting a dense and diverse community of native plants. Credit: Craig Sponholtz

Dig an anchoring trench for the lowest downslope row or two of rock, and place the largest rocks of the structure here to anchor the rocks that will be positioned upslope of them (fig. 10.21B, C). The tops of that downslope row of rock should be close to level with the surface of the surrounding soil to act as a gradually-sloped stabilized spillway for the structure (fig. 10.21B). Compact soil around the rock rows with your feet to lock them in place. Spread native grass seed in at least a 3-foot (1-meter) wide band upslope of the spillway rock, then cover the seed with a single layer of rock mulch. Place rocks tightly against one another, ensuring the tops of the rocks are more or less level across each row. Original concept developed by Van Clothier

Strategy: ROCK-LINED PLUNGE POOL (ZUNI BOWL)

Step one, review these Patterns and their Principles at beginning of chapter 1. The health of a waterway is as strong as its connection to its floodplains

2. *Sediment size and distribution are "tracks" of the flow*
3. *Steep waterways naturally form stepped pools that dissipate energy*
5. *The riffle–run–pool–glide dissipates energy, recharges groundwater, and lengthens life's access to surface water*
6. *Water flows perpendicular to what it flows over*
7. *The speed, depth, and volume of water flow determines what the water can carry*
8. *Everything in a stream is striving to find its angle of repose*
9. *New structures are stronger after being filled in with sediment and vegetation*

A rock-lined plunge pool is a structure built at headcuts to stabilize the lip of headcut erosion and prevent it from migrating upstream (figs. 10.22A-C). The structure is also known as a Zuni bowl and was named and evolved by Bill Zeedyk after he observed the structures built by people of the Zuni Pueblo. It consists of an arc-shaped rock-mulch rundown or sheet flow collector leading into a constructed plunge pool that dissipates the energy of the falling water. The pool is where water will linger the longest, helping establish vegetation to further stabilize the headcut, Zuni bowl, and channel, while providing wildlife with a longer-lasting water source.

Fig. 10.22A. A newly formed headcut where water flow has cut around a gabion that was intended to heal a previous headcut. Gabions frequently fail because they do not readily conform to natural shapes and they do not actively recruit plant growth. Credit: Craig Sponholtz

Fig. 10.22B. A multi-stepped Zuni bowl constructed using locally available rock during a workshop at the Double-Circle Ranch. It was built around and atop the old, failed gabion. Photo and design by Craig Sponholtz, Watershed Artisans

Fig. 10.22C. After one year and several significant flood events, the Zuni bowl has stabilized the 4-foot (1.2-m) headcut with the deposition of sediment and recruitment of dense vegetation. Credit: Craig Sponholtz

The structure converts a single, high waterfall at an eroding headcut (fig. 10.23A) into a series of smaller stepped falls and pools (fig. 10.23B). Depending on the height of the headcut and the size of rock you are using in the structure, you may have multiple stepped pools (fig. 10.22B), or a single fall and pool down to the plunge pool's lower pour-over location (fig. 10.23B). Ideally, each stepped fall/drop should not exceed 18 inches (45 cm), so the taller the original headcut, the more stepped pools are built into the Zuni bowl(s) (fig. 10.22B). The plunge pool is built by placing rows of rocks around the bowl of the headcut up to half the height of the original headcut. Water collects in the rock-lined pool, then pours over the lower end.

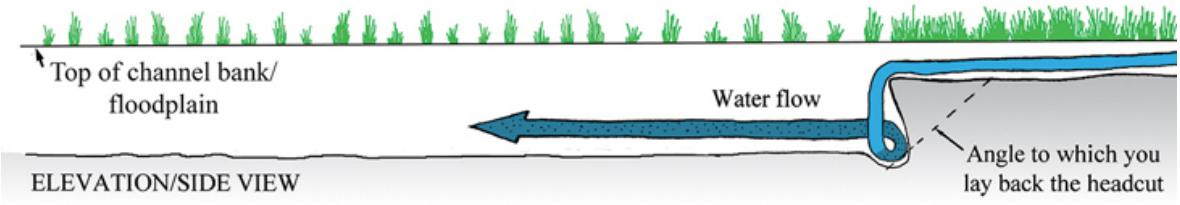


Fig. 10.23A. Side or elevation view of a headcut. Arrow represents water flowing over the headcut. Dotted line represents the more gradual slope the headcut needs to be dug back to before laying rock.

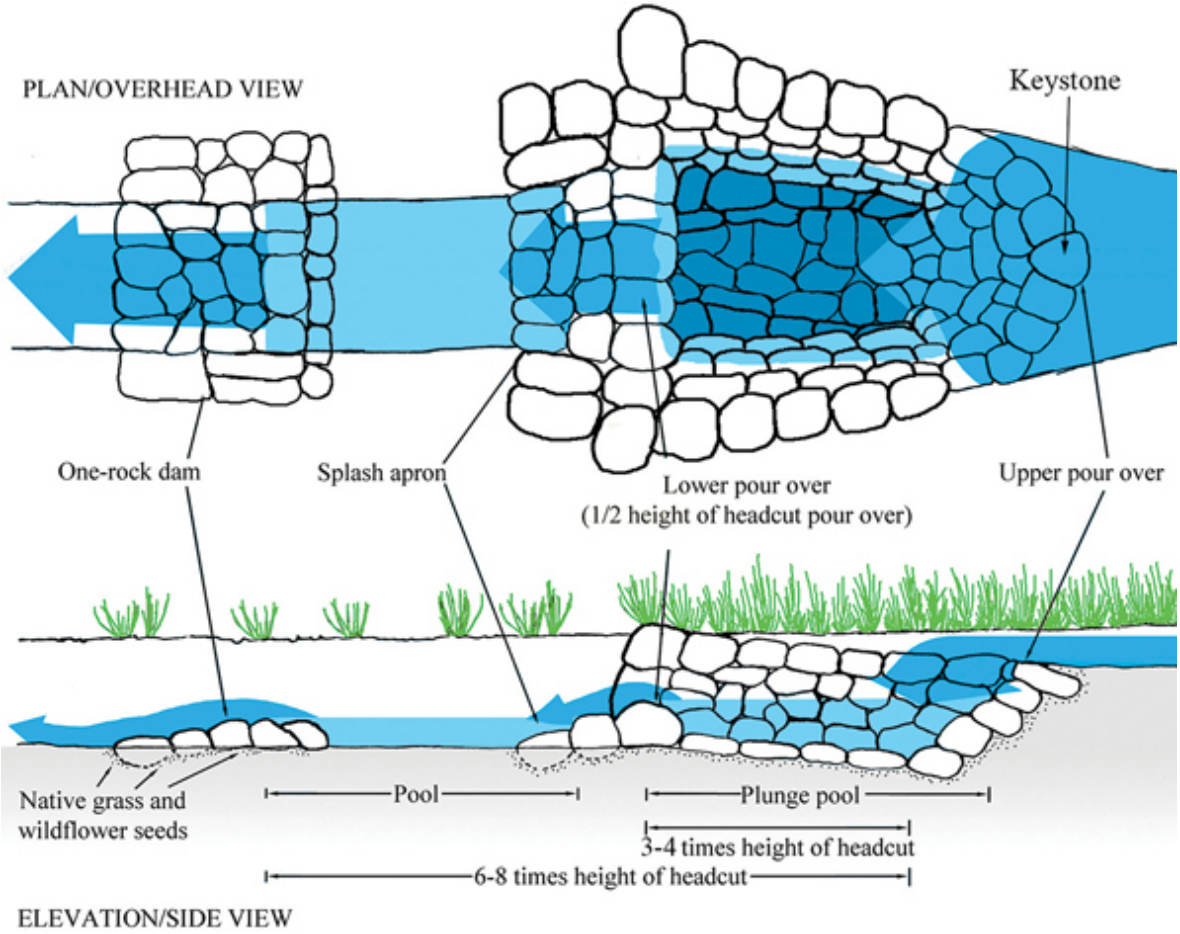


Fig. 10.23B. Overhead and side or elevation view of a rock-lined plunge pool or Zuni bowl with a one-rock dam below. Arrow represents water flow. Downstream from the base of the sloped-back headcut, measure and mark a spot at a distance equaling 3 to 4 times the height of the headcut.[8] Place the largest rocks of the structure here to create the downslope side of a bowl, making the depth of the bowl about half the height of the headcut.[9] Just

downslope of the bowl, construct a splash apron about two rows of rock wide to diffuse the water spilling out of the bowl. To prevent erosive waterfalls, key the lowest splash-apron rock into soil so the top of the downslope-side of rock is level with the bed of the channel. To keep the structure stable, never lay rocks more than one course high. Build out the bowl course by course, like horizontal arches that overlap slightly, but make sure that 3/4 of each rock is in contact with the soil and 1/4 of each rock overlaps the arched row of rock below. All rocks that are stabilizing the rundown to the bowl should be angled/battered into the slope (as you would with a dry-stacked rock retaining wall). The uppermost course of rock should be highest at the downslope ends of the arc and lowest in the middle of the headcut pour-over location to ensure water flows over—not around—the structure. Adapted from *Erosion Control Field Guide*

Like a rock-mulch rundown, a Zuni bowl can be used to stabilize or prevent a headcut from forming at the point where sheet flow is being concentrated into channelized flow. Unlike a rock-mulch rundown, it can also be used within an existing channel or drainage where it can stop a headcut that is cutting the channel deeper. (See figures 10.22A – 10.22C.) Note that a one-rock dam (ORD) is typically built downstream of a rock-lined plunge pool at a horizontal distance that is 6 to 8 times the height of the headcut that the rock-lined plunge pool is stabilizing. This creates a secondary shallow pool of water held by the ORD that further dissipates stream energy (fig. 10.23B).

The upstream end of the structure's upper pour over is built right up to—but not above—the elevation of the uneroded bed of the water flow. It is critical that water flows down and into the structure, not around it (figs. 10.23B, 10.24).

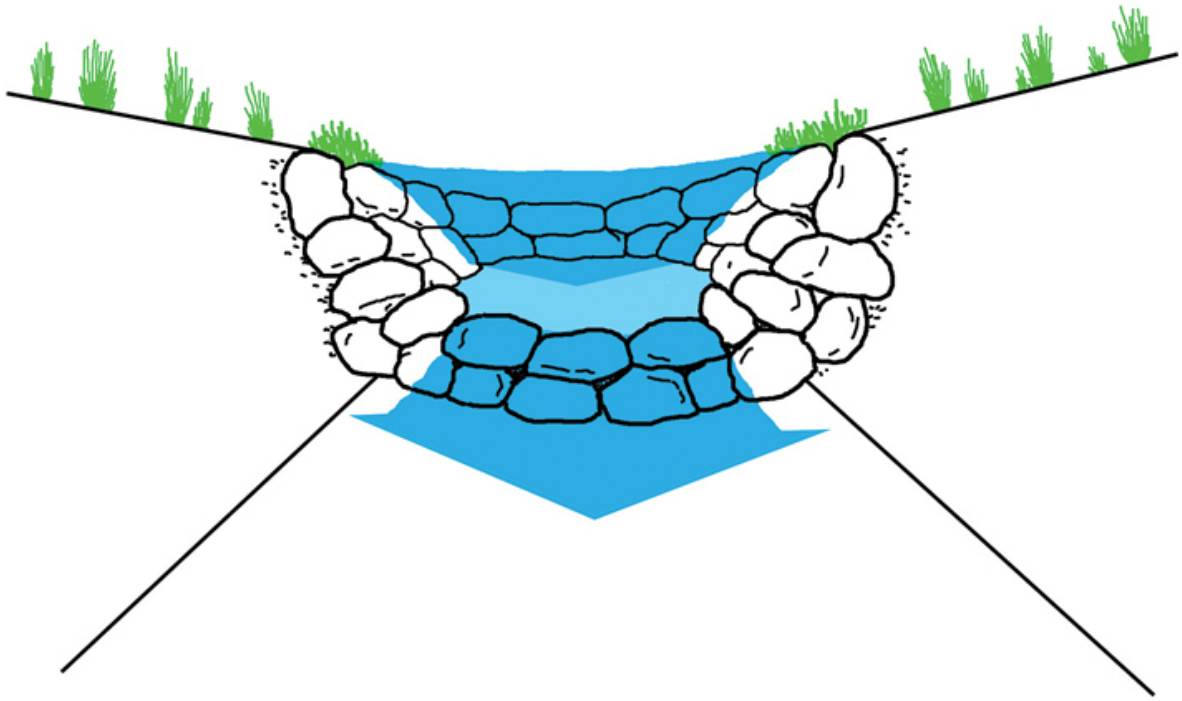


Fig. 10.24. Looking upstream at water flowing over a Zuni bowl. Note how the side arms of the structure rise and get closer to the floodplain atop the channel banks as the side arms move downstream, so the depth and force of the water flowing over the downstream ends of the structure is less than the deeper flow at the center of the structure. The shape—arching into the force of the flow upstream, like an arch in a wall arching toward the weight of the wall or roof above— further strengthens the structure.

Compare fig. 10.23B to fig. 10.10, and note that the first part of the Zuni bowl —the rock-mulch rundown into the pool—is the *riffle-run*. The plunge pool is the *pool*. The lower pour over is the *glide*. And the area from the lower pour-over location to the ORD—which often fills with sediment—is the next lower *riffle*.

Since water flows perpendicular to what it flows over, the upper arms (or "vanes") of the Zuni bowl's arch are angled to redirect water into the center of the channel and the structure's pool. Furthermore, both of the arms of the structure's arch gain in elevation as their ends move *down*stream; so as you move downstream the structures' arms or vanes move higher on the bank and closer to the channel's floodplain. This incrementally reduces the depth, and thus reduces the energy of the water flowing over the upper ends of the structure along the channel's bank, directs overflow water into the center of the channel and the structure's pool, and beneficially backs some of the flood flows up onto the floodplain (fig. 10.24).

Strategy: ONE-ROCK DAMS (ORDs)

Step one, review these Patterns and their Principles at beginning of chapter

1. *The health of a waterway is as strong as its connection to its floodplains*
2. *Sediment size and distribution are "tracks" of the flow*
4. *Gradually sloped waterways typically have meandering flows*
5. *The riffle–run–pool–glide dissipates energy, recharges groundwater, and lengthens life's access to surface water*
6. *Water flows perpendicular to what it flows over*
7. *The speed, depth, and volume of water flow determines what the water can carry*
8. *Everything in a stream is striving to find its angle of repose*
9. *New structures are stronger after being filled in with sediment and vegetation*

A one-rock dam (ORD) is a low barrier or grade-control structure placed perpendicular to the flow of water within a drainage (figs. 10.25, 10.26A,B). It is basically a constructed riffle (fig. 10.10) that slows— but does not stop—the flow of water.

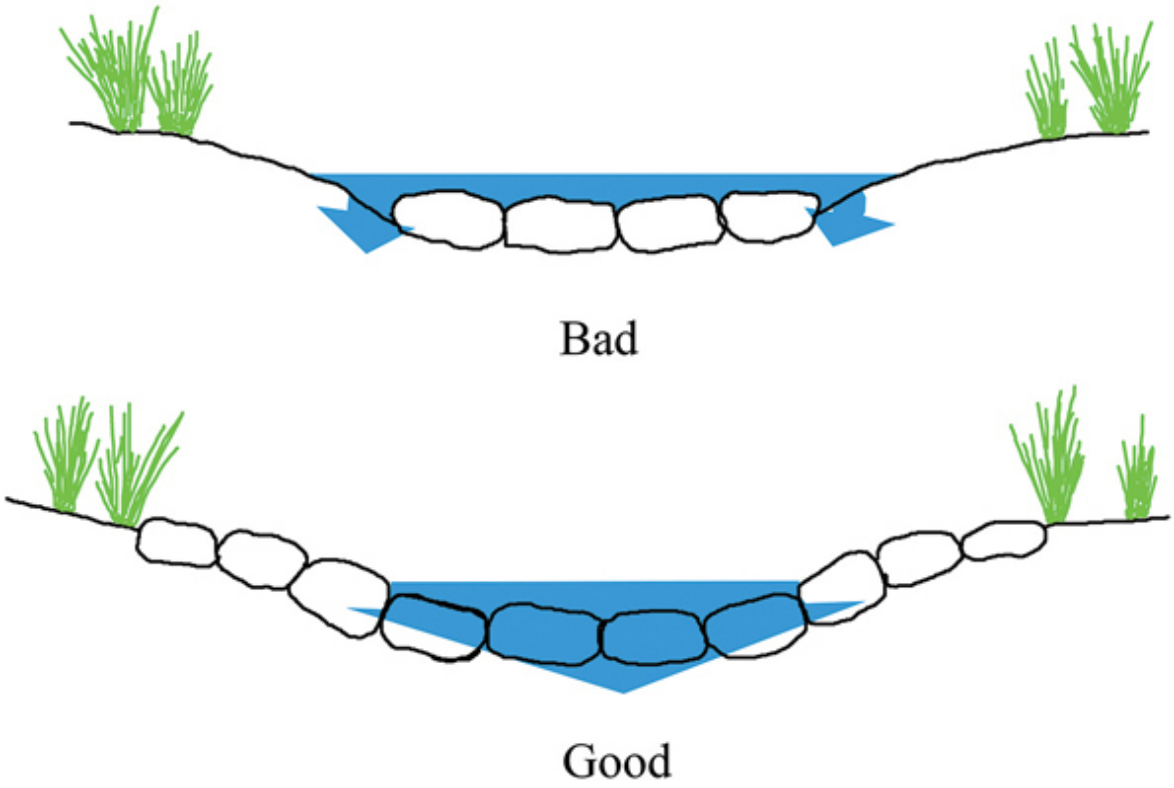


Fig. 10.25. Always maintain a low point in the channel cross section when building a one-rock dam to prevent bank erosion due to water cutting around the structure

Fig. 10.26A. Project site before construction of the one-rock dam (ORD). Craig had built a cross vane and some ORDs upstream of this location to stabilize a road crossing. We decided to build another ORD here to lengthen the transition from the streambed elevation on the upstream side of the structures above to the creek's existing grade below. Additionally, since the banks were slightly incised, we wanted to lift the water slightly to better water the stream-side vegetation.

Fig. 10.26B. After constructing the ORD, note how the width of flowing water has widened and risen upstream of the ORD. This results in more soil-water contact, water flowing closer to vegetation, and broader floodplain flows that can infiltrate into more surface area. The structure is built to curve up the banks so water will flow over the ORD—not around it. The top of the ORD also creates a shallower stream crossing.

An ORD is built across the entire width of a shallow channel and slopes up each bank to ensure water does not flow around its sides (fig. 10.25). It is built just one rock tall and typically does not exceed one foot (30 cm) in height (taller structures are less stable). For strength it should extend five or more tightly packed rock-courses along the channel length. It is built in the shape of a gradually sloped speed hump with the top of the rocks that are in the downstream row placed at the same level as the bed of the channel. Unlike with a check dam or gabion, there is no steep elevation drop on the downstream side that would induce the erosive force of falling water. It is purposefully permeable or "leaky."

ORDs help stabilize the bed of the channel by increasing its roughness, recruiting vegetation within and around the dam, capturing sediment, and *gradually* raising the level of the channel bed over time (figs. 10.26A, B; 10.27A, B, 10.28).[10] Thus they work best in areas with high sediment.

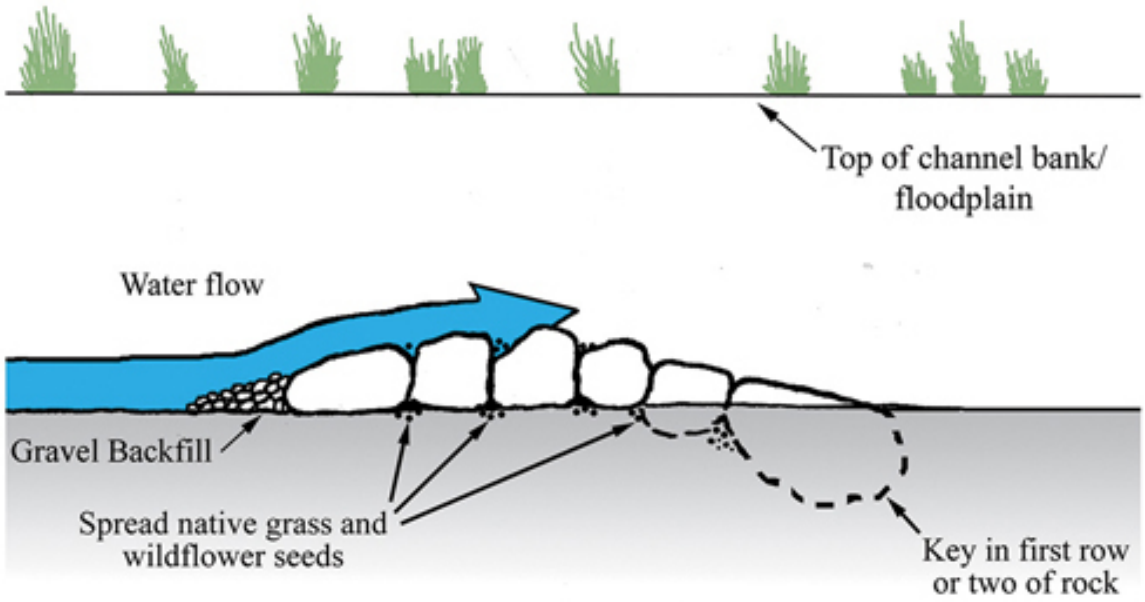


Fig. 10.27A. Elevation/side view of a one-rock dam. Key in the rocks on the first downslope row or two using the largest rocks to anchor the structure. These act as a footer and foundation, and function as a gradual and stable spillway. Avoid creating a steep waterfall-like drop from rock to bare soil where water flow could create a scour hole. Seed the structure with native grasses to speed establishment of anchoring vegetation. To strengthen the structure before it naturally backfills, backfill it manually with small rock and/or gravel, if these are available.

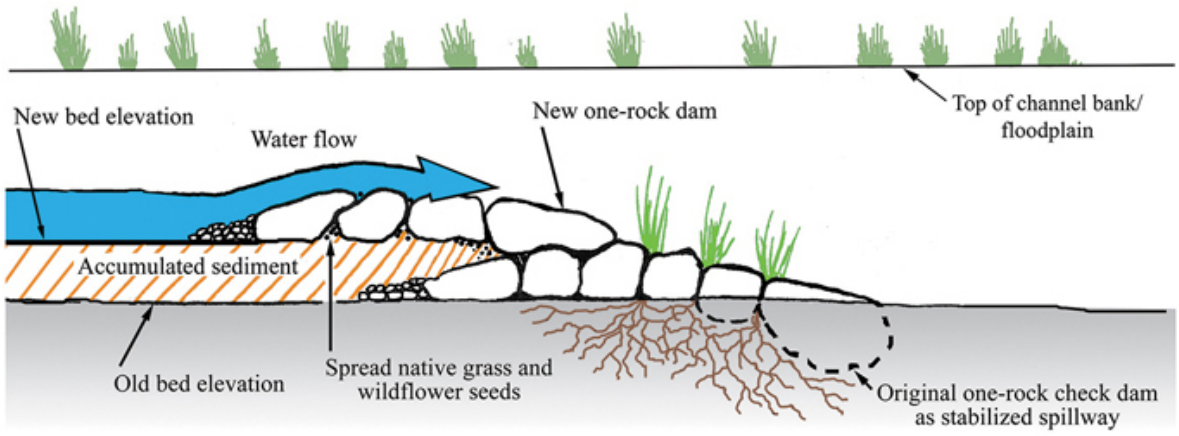


Fig. 10.27B. Another one-rock dam (ORD) can be built upon the first ORD after the first one and all the other ORDs in the series have naturally back filled with sediment and have been stabilized with vegetation. Again, use the largest rocks of the structure to form the downstream row(s). The original ORD then acts as a stabilized spillway for the second. An ORD typically acts as a riffle (see

fig. 10.10). Note how the waterway gradually steepens where the water pours over the dam.

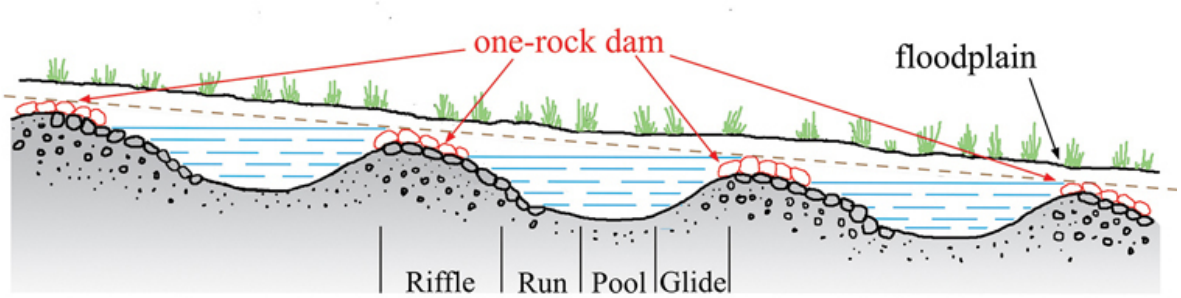


Fig. 10.28. A series of one-rock dams, shown in red, evenly raise the whole bed of the channel, as measured from the top of each riffle crest. The brown dashed line signifies the elevation of the average *fill line*—the level to which sediment can fill pools and raise the channel's bed if it has sediment-rich ephemeral or intermittent water flow. The darker blue line represents the increase in pool depth created by the one-rock dams and the rise in water flow relative to the grassy line of the floodplain. Note: the vertical scale is somewhat exaggerated in this illustration to more easily show the patterns of change in elevations. See fig. 10.10 for a plan view.

Flowing water and sediment slow down and back up behind the ORD, spreading out over the channel bed before flowing through and over the dam. By slowing and spreading the flow of water, ORDs help moisture infiltrate into the soil, reduce downstream flooding by moderating the peak flow of water, retain soil and organic matter upslope of and within the dam, and reduce erosion. They are often used to help heal and even raise the bed of deepening arroyos or gullies. Thus the ORD is a stabilization technique (like a rock-mulch rundown and Zuni bowl), but also a restoration technique (like a sheet flow spreader, described later) in that it both stabilizes erosion and restores previously lost living soil and vegetation.

ORDs can improve roads or paths crossing ephemeral drainages when the dams are built in the channel on the downslope side of the crossing. A "paving" of flat-topped rock can be placed on the road or path surface upslope of the dam to keep the crossing from becoming boggy when wet. Position ORDs in straight sections of a drainageway such as at crossover riffles, not on curves (see fig. 10.10). Original concept developed by Bill Zeedyk.

If any scouring occurs below the structure, this scouring should be repaired by filling the scour hole with another row of rock on the downstream end of the ORD.

Remember patterns and principles FIVE and EIGHT, anytime you lift the streambed with a one-rock dam, you steepen the grade on its downstream side, and as a result you increase the speed of water flow. On the upstream side of an ORD the level of a pool may rise, and the length of the riffle upstream of the pool may decrease. Don't think of a ORD as a single structure. Instead, view it and build it as part of a suite and series of structures (fig. 10.30). Always consider how these relate to, and affect, the reach of the waterway upstream, at, and downstream of the ORD (see fig 10.28 showing a naturally meandering channel and fig. 10.29 showing an unnaturally straight channel). Each ORD is protected by the next ORD downstream. Strive to maintain a constant grade in slopes so there is neither extreme scouring nor extreme sedimentation in any one area of the waterway. By doing this you will even out sediment transport and avoid erosion.

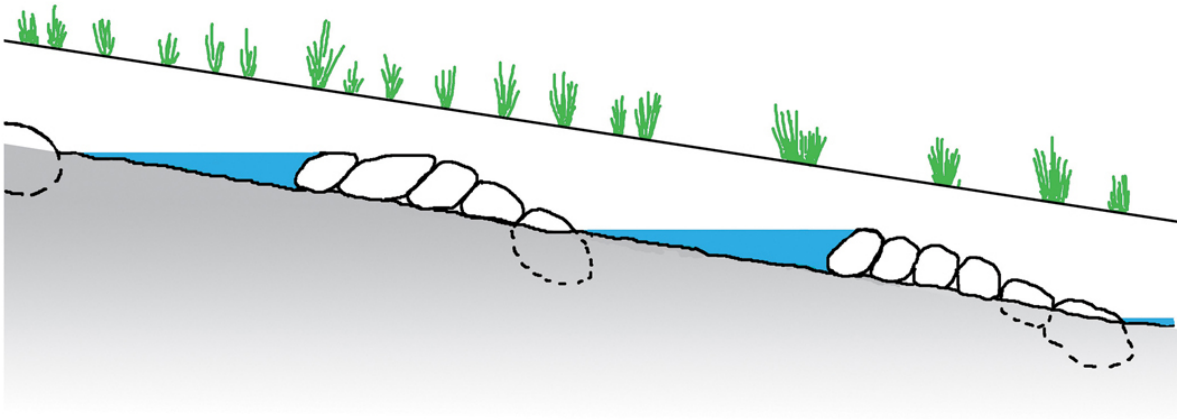


Fig. 10.29. This figure illustrates ORD spacing in an unnaturally straightened channel such as a road-side drainage ditch. The erosive scour effect of water falling/flowing over a steeper surface can be minimized by 1). Lessening the height and steepness of the fall, 2). Creating a stable spillway/apron with downstream rock set at the elevation of the channel bed, 3). Building atop bedrock, and/or 4). Spacing structures so the spillway elevation of the lower structure will back sediment up to the base of the next structure upstream. See fig. 10.28 for spacing in a naturally meandering channel.

Fig. 10.30. This meandering waterway is encouraged to meander still more by placing the low point of the ORD's spillway slightly off center to send a little more of the force of water into the downstream outer bank. There the water gains more sediment to carry to the next structure downstream. At the same time, this lengthens the flow path of water, reduces the slope, and reduces the water's speed. Photo taken just after implementation. Each ORD is part of a suite and series of structures—there are three ORDs in this photo (one at each arrowhead). Designed and built by Craig Sponholtz

Thus within a healthy waterway, the drop in elevation from the top of one riffle–run–pool–glide sequence to the next sequence tends to be relatively constant, creating a uniform channel gradient. To find this gradient, use a transect, laser level, or water level to measure and compare the elevations at each riffle crest relative to a single reference point elevation on the channel bank. Strive to mimic this consistent gradient by building ORDs in a series down the waterway with each ORD constructed to the same height above its riffle crest (fig. 10.28). There should typically be only one ORD per riffle.

The goal is to evenly raise the whole bed of the channel using a series of ORDs of same height rather than using a single ORD to raise only one location in the channel (fig. 10.28). If there is only one ORD, there will be a steeper drop on the downstream side of the ORD, so the riffle–run–pool–glide sequences below it will have to adjust to the greater velocity of water spilling over this taller, steeper ORD. Similarly, when laying out a project it is important you don't omit placing an ORD where a riffle should be. This reiterates the importance of keeping the same drop in elevation from riffle to riffle. The more scoured the channel, the more important this becomes.

Stop building ORDs in a series once the reach of channel you are working in transitions to a different channel type, such as becoming wider, narrower, deeper, or more braided (see the book *Let the Water Do the Work* by Bill Zeedyk and Van Clothier for more on channel types). If you stop at a property line, add a second, lower ORD to make the last drop more gradual and to increase stability. If you stop at a headcut, stabilize that headcut with a Zuni bowl or rock rundown.

See weirs in box 10.3 later in the chapter for a structure similar to an ORD made of wood.

Strategy: FILTER DAM

Step one, review these Patterns and their Principles at beginning of chapter
1. The health of a waterway is as strong as its connection to its floodplains
2. Sediment size and distribution are "tracks" of the flow
6. Water flows perpendicular to what it flows over
7. The speed, depth, and volume of water flow determines what the water can carry
8. Everything in a stream is striving to find its angle of repose
9. New structures are stronger after being filled in with sediment and vegetation

A filter dam is a large and sturdy one-rock dam (ORD) with progressively smaller backfill ranging from large boulders to smaller boulders to large rocks to smaller rocks to cobbles to gravel. The backfill acts as a filter, capturing sediment from the water's flow while letting the water slowly seep through the structure. Should the larger boulders or rock on the structure's downstream side move or settle, the smaller rock, cobble, or gravel on the structure's upstream side will fill in the resulting gaps in the structure (fig. 10.31).

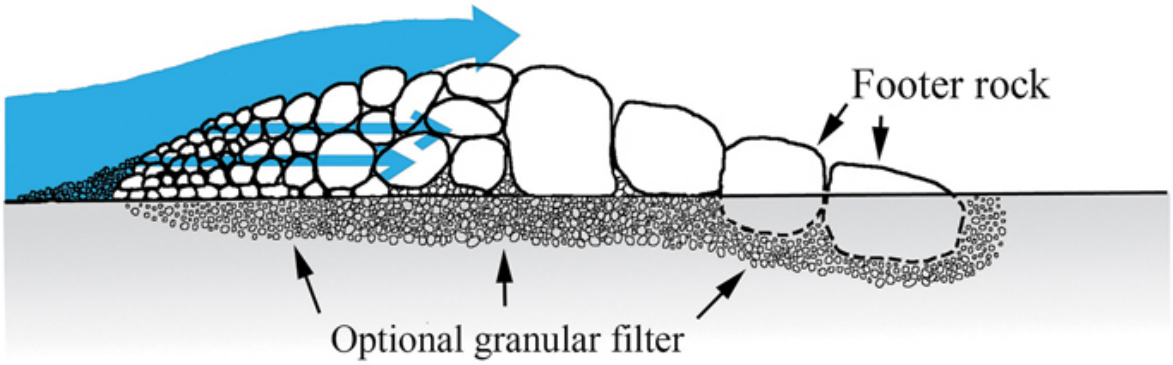


Fig. 10.31. Filter dam. In sand, silt, or high clay channels, a granular filter of unwashed mixed-sized gravel can be placed under the entire structure. Course natural fiber mesh can be used if gravel is not available.

Ample course sediment is needed in the waterway for filter dams to work correctly. Insufficient waterborne sediment would make this structure ineffective. For example, in a channel within a watershed of dense, healthy grasslands, sediment will likely consist only of fine particles, thus a filter dam would likely not fill in correctly and would not be the strategy of choice.[11]

I love to build these on bedrock where they can often create ephemeral seep springs (appendix 1, Volume 1). Water is retained within the sediment on the structure's upslope side then slowly seeps through the structure until it emerges at the dam's downstream base atop the bedrock. This water can flow for days, weeks, or even months after the last big rain.

When filter dams are built on top of bedrock, no footer rocks or boulders are needed. If they are not built on bedrock, then you do need footers. More aggressive filter dams can be built using boulders to gain more height. To prevent water from cutting channels around the sides of the structure, extend the structure into notched banks that are filled with boulders.

A granular filter of mixed particle-size gravels can be placed under the entire structure to prevent excessive settling, to prevent rock from excessively sinking into wet clay soils, and to keep water from piping beneath or through the structure in sand or silt channels (box 10.2). A course natural fiber mesh such as burlap or jute can be used if gravel is not available. You can also place a sheet of mesh vertically across the structure between two rows of the largest rock above grade on the dam's downslope side. This will further ensure that finer-grained material doesn't wash through gaps in the rock.

Strategy: SHEET FLOW SPREADER

Step one, review these Patterns and their Principles at beginning of chapter
1. The health of a waterway is as strong as its connection to its floodplains
2. Sediment size and distribution are "tracks" of the flow
6. Water flows perpendicular to what it flows over
7. The speed, depth, and volume of water flow determines what the water can carry
8. Everything in a stream is striving to find its angle of repose
9. New structures are stronger after being filled in with sediment and vegetation

A sheet flow spreader, also called an *ends up media luna* (crescent moon), is a crescent-shaped rock-mulch structure used to create or enhance a depositional area where the channel widens and the channelized flow can transition to calmer, more spread out sheet flow. Innovator Van Clothier first introduced me to the media luna, and explained how the landform determines its placement and shape. He said it was designed to mimic the depositional pattern of alluvial fans.

To build the structure, lay out the location of its downslope edge by using leveling tools (appendix 1) to find a level contour line across the channel where the landform is beginning to spread the flow out (or at least allows it to do so). This is the opposite of a sheet flow collector, which is placed on contour where the land-form is beginning to channelize the water flow.

Once you've marked your contour line, ensuring its level length is at least four times the width of the current channel, then extend the two ends at least 2 feet (0.6 m) upslope to ensure you'll capture and focus water flow over the wide, level middle section of the structure and prevent water from cutting around the ends. Dig a footer trench to anchor the first downslope row or two of rock, placing the largest rocks of the structure here to anchor all the materials above. As with a one-rock dam, the tops of that downslope row of rocks should be close to level with the surface of the surrounding soil to act as a gradually sloped, stabilized spillway for the structure (fig. 10.27A). Compact soil around the rock rows with your feet to lock them in place. Spread native grass seed in at least a 3-foot (1-meter) wide band upslope of the spillway rock, then cover with a single layer of rock mulch placed atop the soil and seed—not bedded within it. Place rocks (typically at least grapefruit size) tightly against one another, ensuring the tops of the rocks are level (figs. 9.2, 10.13, 10.21B, 10.43, and chapter 3 of Volume 1). Water will flow through and over the structure, spilling out along the entire width of its wide, level middle.

Sheetflow spreaders can also be built from brush in places where rock is not available (figs. 10.32A, B).

Fig. 10.32A. Brush sheet flow spreader placed atop bare eroding ground. Great Barrier Reef Region of Queensland, Australia. Design and photo by Craig Sponholtz. See fig. 10.43 for a one rock-high sheet flow spreader.

Fig. 10.32B. Vegetation growing through the shelter of the slowly decomposing brush sheet flow spreader one year after construction. Design and photo by Craig Sponholtz

BRUSH STRUCTURE TIPS

- *Place cut ends of prunings facing upslope, and branch tips downslope, so water flow pushes branches and their tips into the channel bed to better anchor the structure.*
- *Prune the underside of brush to increase the amount of brush that will be in direct contact with the soil.*
- *Where you prune, you could leave stake-like stubs that can be pressed or hammered down into soil.*
- *Pack brush tightly together, but not too deep. As it drops its leaves you want enough to penetrate the brush to germinate the seeds of vegetation that will grow up through structure.*
- *The longer the prunings, the more contact they will have with the soil and the more stable the structure will be.*
- *When used in channels, avoid use in close proximity (less than 100 times the channe width) to road crossings, bridges, or culverts that might be damaged or clogged by lo material floating downstream.*

- *If rock is available, and depending on channel size, rock could be placed on the pruning's "trunks" and larger branches to further hold them in place.*

Box 10.3. Induced Meandering

An integrated strategy to consider in abnormally straight, eroding channels is "induced meandering." This strategy speeds up the widening of narrow incised channels and gullies, lengthens the flow path, and reduces channel depth as the waterway erodes its banks in a natural meandering pattern.

This concept was applied in the Pueblo Colorado Wash at the Hubble Trading Post National Historic Site in northeastern Arizona. As a result, the once gullied waterway, which had dry and barren-to-patchy stream banks, now supports lush stands of cottonwood and willow trees. The streambed has aggraded, groundwater levels have risen 11 feet (3 meters), wetland plants abound, and there are perennial pools of water (figs. 10.34A, B).

Your guide to this strategy is the book *Let the Water Do the Work: Induced Meandering, an Evolving Method for Restoring Incised Channels* by Bill Zeedyk and Van Clothier—a must read if you are attempting this. This section is adapted from that book. I include it here to give you just enough information to begin to grasp the concept and see how the forms and placement of its structures are informed by natural patterns of water and sediment flow.

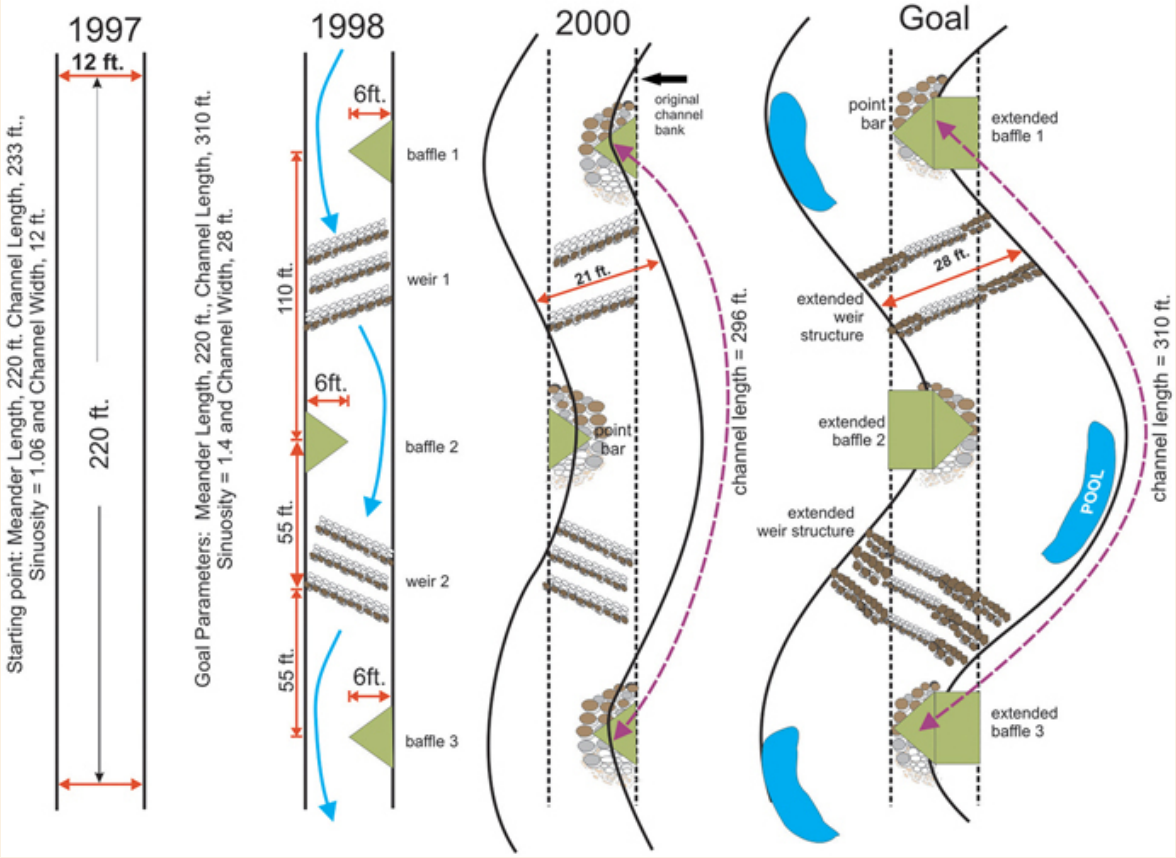


Fig. 10.33. The effect of induced meandering at Hubble Trading Post National Historic Site, shown between 1997 and its future goal. Reproduced with permission from *Let the Water Do the Work* by Bill Zeedyk and Van Clothier

Fig. 10.34A. Before induced meandering work. Degrading, gullied Pueblo Colorado Wash at Hubble Trading Post National Historic Site, northeastern Arizona, May 28, 1998. Invasive Russian olive trees on left. View east from south bank, 50mm lens used. Credit: Bill Zeedyk. Reproduced with permission from Quivira Coalition's *Resilience*, No. 41, August 2015

Fig. 10.34B. After induced meandering work. Aggrading Pueblo Colorado Wash at Hubble Trading Post National Historic Site, June 12, 2015. Groundwater levels have risen 11 feet (3 meters), wetland plants abound, and there are perennial pools of water. Invasive Russian olive trees have been removed. Credit: Tamara Gadzia. Reproduced with permission from Quivira Coalition's *Resilience*, No. 41, August 2015

In the induced meandering context, a *weir* mimics and induces the formation of a *riffle–run*. It is constructed at a skewed angle rather than straight across a waterway so the water flowing over and perpendicular to it will be directed into the downstream bank (figs. 10.33, 10.44). It can be made of rock (ORD), wooden posts woven with flexible branches, a combination of woven wooden posts and rock, or boulders (fig. 10.35). When weirs are properly placed and sized relative to the planned channel dimensions, slope, and meander patterns (see *Let the Water Do the Work* for how to do this), they will be temporary in nature. Over time the waterway's flow will replace them with a natural *riffle–run* sequence.

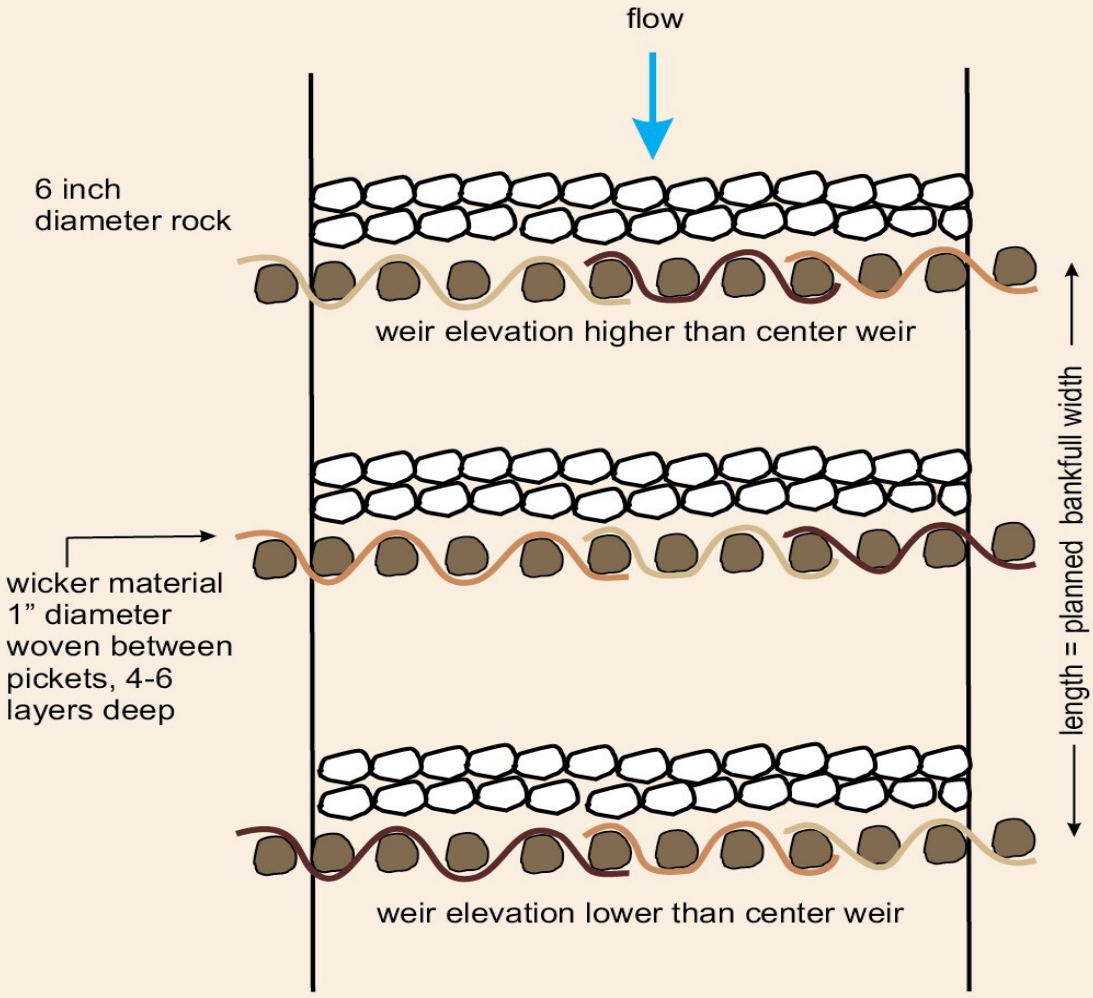
Wicker weirs are well suited to sand, silt, and clay channel beds. In this context, rock structures must have substantial footers built down to four or more times the scour depth that can occur in big flows. To avoid this substantial cost and potential instability, wooden posts—ideally made from onsite material—are preferred. These can be driven far below the scour depth, trimmed to the proper height after placement, then woven with 1-inch (2.5-cm) diameter branches 4 to 6 layers deep. If your channel has rock, use rock weirs since you will not be able to drive posts in. If it is sand, silt, or clay, use posts.[12]

Boulder weirs are well suited to gravel and cobble channel beds. To resist scour, the downstream row of boulders should be buried to their tops to act as a footer, anchoring the rest of the boulders. Boulders are placed tight against one another and buried to half their

height in a trench. An ORD is a variation of a boulder weir and is best suited for streams and gullies less than 15 feet (4.5 m) in width.

A *baffle* mimics and induces the formation of a point bar (figs. 10.10, 10.33, 10.36, 10.44, 10.45), thus you could call it a "point bar starter kit." Baffles reduce the speed and depth of water flow along a channel bank, while concentrating deeper, faster flow along the opposite bank. Some of the sediment eroded from the opposite bank then deposits on the baffle and begins to form a point bar. As the point bar is colonized by vegetation it becomes more resistant to erosion, more effective at capturing more sediment, and more effective at deflecting water toward the opposite bank.

A *baffle* can be built of the same materials as a weir. It is typically constructed as a 30° - 60° right triangle. As stated in *Let the Water Do the Work*, "The triangular baffle is configured so that the short leg (A) protrudes outward from the bank toward mid channel (width); the long leg (B) forms the base of the structure parallel with the bank (length): and the hypotenuse (C) forms the face of the structure which serves to deflect or wedge flow toward the opposite bank. To emulate the vertical dimensions of a point bar, the upper surface of a baffle must taper downward from the edge of the streambank to mid-channel. At the bank, the top of the baffle should be level with bankfull stage (D); and the tip should be no higher than one-third maximum bankfull channel depth" (fig 10.36).[13]


flow
6 inch
diameter rock
weir elevation higher than center weir
wicker material
1" diameter
woven between
pickets, 4-6
layers deep
length = planned bankfull width
weir elevation lower than center weir

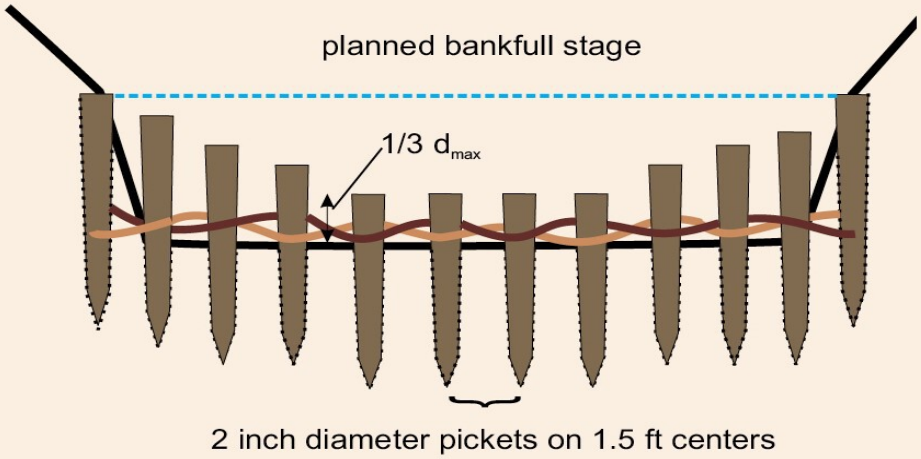

planned bankfull stage
1/3 d_{max}
2 inch diameter pickets on 1.5 ft centers

Fig. 10.35. Wicker weir schematic. In plan view (top), wicker material averaging 1-inch (2.5-cm) in diameter is woven between pickets, 4-6 layers deep. The cross section (bottom) shows pickets driven 3-5 feet (0.9-1.5m) into a streambed with the height of mid-channel pickets at 1/3 the maximum bankfull depth. Reproduced with permission from *Let the Water Do the Work*

Induced Meandering flattens the grade of the creek—the longer the channel, the less the grade, and the slower the flow. Its like a slow moving novice skier taking a wider more meandering path down a slope than a fast moving experienced skier. So a wider channel is needed to handle the same volume of the now slower moving water. But if you have too much sinuosity and the water moves too slow for the width of the channel, flow can cut through the point bar, making the channel shorter and deeper. This response determines how much sinuosity the channel will sustain over the long run, which informs the principle *the alignment of the stream is the balance between the force of the moving water and the resistance of the bank*. The easiest way to screw up is to make meanders too abrupt. So err on the side of more gradual, longer meander bends.

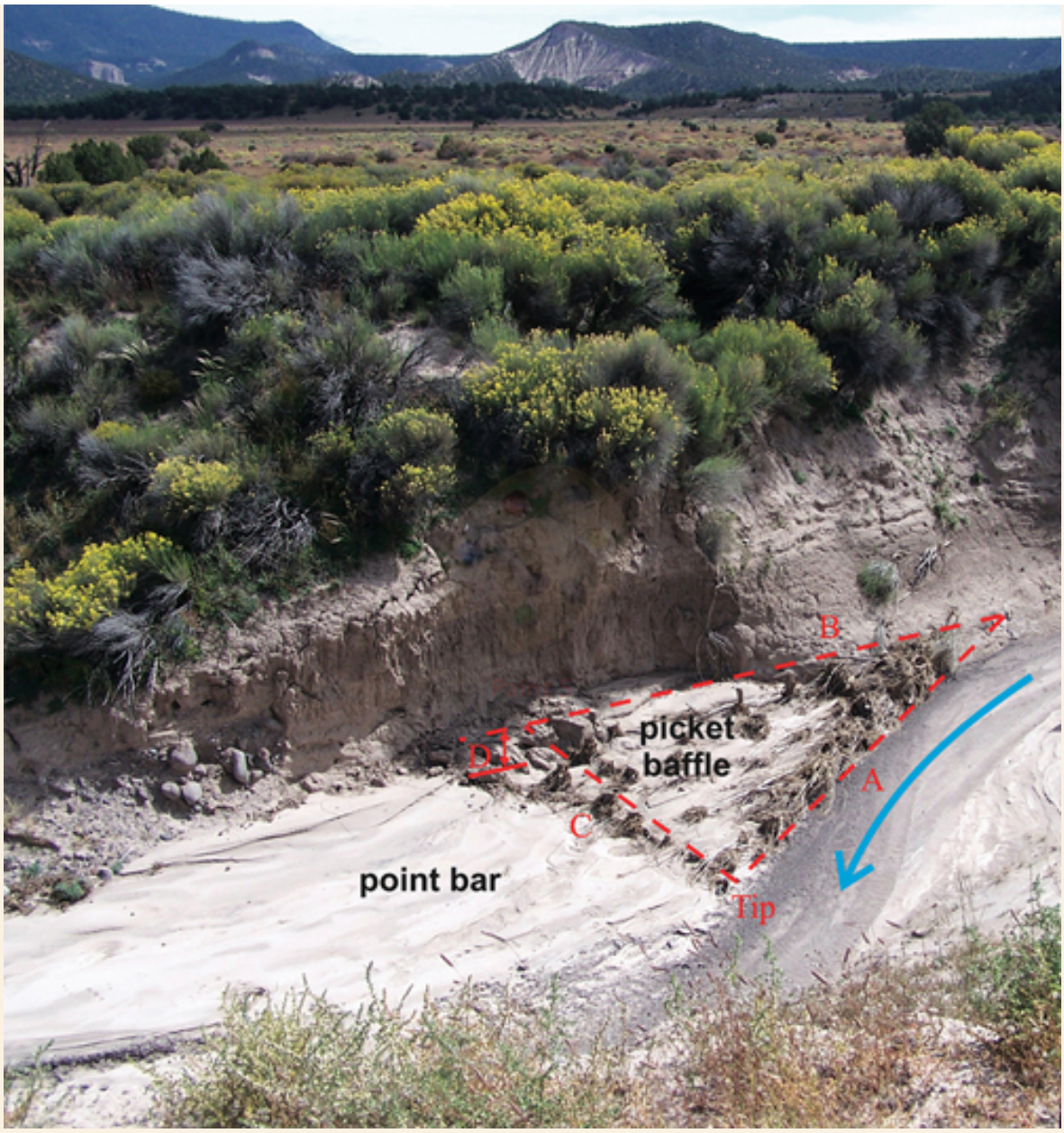


Fig. 10.36. A picket baffle evolving a point bar after two flood events, Loco Creek, Catron County, New Mexico. Photo: Kirk Gadzia. Reproduced with permission from *Let the Water Do the Work*

Box 10.4. The Role of Beaver and other Keystone Species in Watershed Health

Reproduced with permission from *Basins of Relations: A Guide to Protecting and Restoring Our Watersheds, 3rd Edition* by Brock Dolman and Kate Lundquist

Fig. 10.37. Beaver dam, Child's Meadow, California.
Credit: Brock Dolman from *Beaver in California: Creating a Culture of Stewardship.*

Every watershed supports a wide variety of flora and fauna. Some species disproportionately benefit those living in their midst. Biologists call these "keystone species" because if they were to be removed the ecosystem would change drastically. Citizens wanting to contribute to the health of their watersheds are wise to identify who the keystone species are in their basin and learn about the benefits, or "ecosystem services," they provide. Supporting these contributors is a great way to help our watersheds thrive.

To better understand how we can steward these species it is important to learn about their current status and what threats, if any, they are facing. Acting to ensure the health of these species and removing barriers that prevent them from contributing their services is a cost effective way to enhance watershed function and even accelerate restoration.

Several of California's Pacific coast lamprey and salmon function as keystone species due to their "anadromous" life cycle. This means they are born in freshwater, migrate to the ocean to mature and then return to freshwater to reproduce and die. Their carcasses provide an important source of marine derived nutrients that contribute to the health and productivity of those who eat them and the watersheds where they live (fig. 10.38). Invertebrates, birds and mammals eat and then distribute these minerals across the watershed. Without salmon and lamprey, many inland forests and their inhabitants would become deficient in these critical nutrients that are more abundant in marine ecosystems.

Pacific coast lamprey and salmon require clear, cold and copious fresh water to survive. These important fish are struggling to survive in California. We need to do everything we

can to protect the ones we have left and restore our watersheds to support their recovery into the future.

Fig. 10.38. This salmon returned from the ocean, reproduced and then died, making its marine nutrients available to this freshwater ecosytem. Credit: Brock Dolman

Fig. 10.39. Beaver in Tulocay Creek, Napa County, California. This beaver is eating a willow shoot. Credit: Rusty Cohn

A native keystone species that could help bring salmon and Pacific coast lamprey back is the North American beaver (*Castor canadensis*) (fig. 10.39). Once abundant across the

continent, beaver were nearly hunted to extinction in the 1800s because their fur was used for making hats and coats. They are now making a slow comeback and warrant protection.

Beaver are wetland engineers who physically modify the environment more than any other nonhuman organism in the northern hemisphere. The dam complexes, bank burrows, canals and food caches they build have physical and biological effects on the watershed, changing how water flows across the landscape, and creating habitat for many rare, threatened and endangered species.

The dams they build spread and slow the flow of water across the landscape, reconnecting this water with the floodplain and encouraging it to rehydrate riparian corridors and their associated meadows and wetlands. When beaver dams spread the water out, creating wetter habitat, they also promote subterranean recharge and the release of water later in the season to enhance base flows. These benefits are especially important now that loss of snow pack and persistent drought are predicted to increase in frequency and intensity.

In addition to increasing the presence of water, beaver dams have the ability to enhance water quality by trapping sediment, excess nutrients and even contaminants. One or several dams on a creek or river can act as a buffer in high flows, reducing the intensity of floods. Beaver dams slow and redirect floodwaters across adjacent low lands, encouraging riparian vegetation, which also works to accumulate soil materials and hold existing soils in place. These beaver wetlands can help sequester carbon.

The landscape modifications beaver make create important habitat for a wide variety of plants, insects, amphibians, reptiles, birds and mammals. Bank burrows, lodges, food caches and dams provide cover for aquatic species. These wetlands are teeming with life and provide food and water for many threatened and endangered species such as the Red-legged frogs, Coho salmon and the Willow flycatcher.

While some landowners get frustrated with beaver modifications [*such as their chewing on trees or raising water levels*], there are many inexpensive solutions for mitigating potential damage. When you weigh the benefits, you soon learn that stewarding beaver can be a cost-effective way to increase biodiversity, enhance water quality and quantity and restore riparian and wetland ecosystems.

Humans have an enormous impact on the environment and, if given the proper tools can function as a keystone species as well. How we live our lives can have a huge effect on the watershed. Every day we have the opportunity to make choices that can either harm or benefit the earth's ecosystems.

For more on beaver including many resources on how to collaborate with, and effectively manage them see Beaver in California: Creating a Culture of Stewardship *by Kate Lundquist with Brock Dolman, oaec.org/water.*

MORE REAL-LIFE EXAMPLES

DON JOSE STORM*DRAIN* TURNED STORM*PARK*

Stormdrain outlets are all too often eroding, litter-strewn blights. But they can be amazing water sources for stabilizing life and beauty—they can even be stormwater-irrigated parks. Craig Sponholtz of Watershed Artisans proved this in the high desert city of Santa Fe, New Mexico, where the Don Jose storm-drain

discharges sediment-rich runoff from a residential neighborhood into the ephemeral Santa Fe River beside a riverside path network.

Primarily using an excavator with a bucket and thumb, Craig turned the erosive gully below the storm-drain outlet (fig. 10.40A) into a series of stepped basins beautifully lined with boulders and rocks, creating wonderful seating and gathering areas for use in dry times (fig. 10.40B). The basins were dug to 6-foot (1.8-m) depths to increase their capacity. To further spread the basin water, Craig laid 3-inch (75-mm) diameter perforated plastic drain pipe at the bottom of a number of the basins. The drain pipe was wrapped in landscape fabric to keep fine sediment from clogging the perforations. This drain pipe was then extended laterally via subsurface infiltration trenches. These trenches were dug beneath planting terraces on either side of the basins in order to provide a passive subsurface irrigation system (see chapter 5 for basic concept) for native plantings such as ponderosa pine trees. The basins were then filled with a 3-foot (1-m) depth of pollutant-filtering wood chips that had been inoculated with beneficial mycelium. They were then topped with a single course of 6-inch (15-cm) diameter cobble rock to hold the materials in place.

Fig. 10.40A. Don Jose storm*drain* outet before treatment, March, 2012. Credit: Craig Sponholtz

Fig. 10.40B. Don Jose storm*park* outlet after treatment, May 2012. Treatment consisted of a series of stepped basins with rock step-downs acting as the "riffle and run" between pools. A temporary gravity-fed drip irrigation system was attached to a water tank hidden behind a wood "coyote" fence atop the culvert outlet to help get plants established the first two years after planting.

Fig. 10.40C. Don Jose storm*park* flow during a storm in 2014. To reduce graffiti, Craig hired a well-known local street artist, Mateo García, to paint the walls of the stormdrain outlet. With plantings now established, the water tank feeding the temporary gravity-fed drip irrigation system has been removed. Credit: Craig Sponholtz

To establish new plantings, irrigation was provided for the first two years using a temporary gravity-fed drip irrigation system attached to a water tank hidden behind a wood "coyote" fence atop the culvert outlet (fig 10.40B).

At the bottom of the stepped basins, a sheet flow collector spreads out the flow into an alluvial fan stabilized and enhanced by native willow and cottonwood trees. A once eroding liability has become an oasis-like extension of the river park that keeps getting better with every year of stormwater-irrigated growth.

THE TRANSFORMATION OF CEBOLLA CREEK

By Kristina G. Fisher and Michael Scialdone *Reproduced with permission* from *It Works!: A Celebration of Bill Zeedyk's 80th Year*, *Resilience: A Voice of the New Agrarianism*, No. 41, *August 2015. Quivira Coalition*

It takes an impressive sense of vision and time to see the possibility of a wetland in a landscape that consists of a mud pit around an old spring and miles (kilometers) of gully downcut forty feet (12 m) or more (fig 10.41A).

10.41A. Workshop in the large gully 2006. Credit: D. Muirhead
Compare to fig. 10.41B

But realizing this sort of vision is Bill Zeedyk's specialty. Over the past eighteen years, he has led an effort to restore the degraded wetlands of Cebolla Canyon in the El Malpais National Conservation Area near Grants, New Mexico. The results achieved so far have been remarkable—particularly considering that much of the work has been completed by volunteers (fig. 10.41B).

10.41B. Vegetation response in gully bottom 2010. Credit: K.G. Fisher
Compare to fig. 10.41A

The Story of Cebolla Canyon

Cebolla Canyon lies in the southeast section of the El Malpais National Conservation Area. Approximately five miles up the canyon sits Cebolla Spring, a perennial spring that, along with the summer monsoon rains, created a substantial slope wetland in an otherwise very arid area. The wetland fed a series of wet meadows extending down the broad valley floor of Cebolla Canyon.

Archeological evidence indicates that the canyon was used as a campsite as far back as 10,000 B.C., and it was periodically inhabited and farmed since at least

400 A.D. Due to climate change, early pueblo farms were abandoned by the mid-1300s.

During the 1930s, another shift in the climate led to big changes in Cebolla Canyon: homesteaders fleeing the Dust Bowl settled there, building houses and a school and growing truck crops including potatoes, radishes, carrots, cabbages, and beets. They also raised chickens for eggs and cut firewood sold in Grants. The homesteaders chose Cebolla Canyon because of the perennial spring, from which they hauled water and built diversion ditches to irrigate fields.

Not long after it was settled, the community was abandoned. With the onset of World War II, most of the men left to join the military and the women took jobs in factories. Unfortunately, some of the changes the homesteaders had made continued to impact the canyon for decades.

Aerial photos taken by Charles Lindbergh during his surveys of New Mexico in the late 1930s show the dirt roads the homesteaders carved into Cebolla Canyon. In the years that followed, these roads captured the annual monsoon flows, became new water channels, and began to downcut. As the gullies cut through the wet meadow vegetation, the water table sank to follow them; soon the roots of the once-dense vegetation dried out and wetland plants were replaced by more sparse arid-adapted upland species. The now exposed fine silt and sandy soil eroded easily and the gullies continued to cut, dropping as much as 50 feet (15 meters) below the valley floor by the late 1990s. These impacts were exacerbated by the abandoned gully-like irrigation ditches, which continued to steadily drain the wetland, and unmanaged grazing, which saw cattle trailing up the gully bottom and wallowing in the small mud pit that had replaced the wetland around the spring.

In 1987, the El Malpais National Monument was created and much of the area around Cebolla Canyon was designated as wilderness. However, part of Cebolla Canyon itself remained privately held until 1995, when it was acquired by the federal government and placed in the hands of the Bureau of Land Management (BLM). Within a few years, Bill Zeedyk began arranging partnerships between the BLM, the New Mexico Environment Department, and several nonprofits with the goal of restoring Cebolla's historic wetlands.

Albuquerque Wildlife Federation's Involvement

One of those nonprofit groups was the Albuquerque Wildlife Federation (AWF), an all-volunteer organization founded by Aldo Leopold in 1914 and dedicated to

protecting and restoring wildlife habitat in New Mexico.

A key part of getting volunteers to come out (and come back) to restoration projects is visionary leadership, and in this AWF has benefitted tremendously from Bill Zeedyk. Not only has he mentored AWF volunteers in a wide variety of induced meandering riparian restoration techniques, but he also brings an uncanny ability to read the landscape, imagine what it can become, and communicate that to others.

Bill first brought AWF volunteers out to Cebolla Canyon in the year 2000. Both authors remember our first impressions of the canyon, feeling overwhelmed by the extent of the damage and pretty hopeless about the prospect of turning this landscape of dusty gramma grass and rabbit brush into a thriving wetland. However, in fairly short order, the changes we saw on the land surpassed our expectations, and we began to share in Bill's vision and excitement about how this place might recover. AWF volunteers have eagerly returned to Cebolla Canyon just about every year for the past decade and a half.

Restoration Techniques

The restoration work at Cebolla Canyon focused on three goals: halt the downcutting of the gullies, expand the wetland habitat, and increase water infiltration and storage in the meadows.

The first restoration project involved constructing a seven-acre (2.8 ha) fence exclosure around Cebolla Spring, which at that time emptied into a stock pond and lacked any wetland vegetation.

In 2000, AWF volunteers came out for our first work weekend at Cebolla Canyon, which focused on plugging some of the old irrigation ditches that were draining water from the spring into the main Cebolla Canyon gully. Volunteers also filled in other ditches, gullies, and cattle trails downstream from the spring and built restoration structures designed to hold water on the landscape and keep the meadows wetter.

The following year, seeing the wetland recovering inside the original exclosure, the fenced area was enlarged.

From 2002-2004, AWF volunteers continued to focus on the upper meadows where the gullies were shallow, building numerous one-rock dams, Zuni bowls, and media lunas, as well as several "burrito dams" in areas that lacked rocks (fig. 10.42).

Fig. 10.42. AWF volunteers constructing a burrito dam.
Credit: G. Muirhead

Fig. 10.43. Working on a sheet flow spreader media luna.
Credit: K.G. Fisher

To build a burrito dam, volunteers brought sandbags, filled them with dirt on-site, and stacked them one-layer deep just as we would do with rocks in a one-rock dam. The sandbags were then wrapped in a layer of UV-resistant cloth (the tortilla of the "burrito") to hold them together and keep them from falling apart in the

sunlight. To keep elk from damaging the structures, they were topped with downed tree branches. The burrito dams were so successful at capturing sediment and growing vegetation, after a year or two these branches became the only signs of the structures.

From 2005-2008, AWF volunteers worked to arrest the downcutting of the gully in some of its deepest sections, in a reach stretching about a mile and a quarter (2 km) upstream from the riparian exclosure fence. In this reach, AWF volunteers built dozens of one-rock dams and wicker weirs across the bottom of the channel to slow down the water and capture silt (figs. 10.44, 10.45). Volunteers also built a series of picket baffles and vanes to push the water from one side of the gully to the other, creating meanders and knocking down huge piles of sediment to be captured by the one-rock dams. As we knocked down the side embankments of the gully, we were also widening the bottom of the channel, giving the water more room to spread out, slow down, and seep in. This widening also created space for stands of willows and bulrushes, which colonized the area on their own as conditions improved. Harvesting from these pioneers, we planted more of them in and around some of our structures.

Fig. 10.44. Picket baffle, wicker weirs, and another picket baffle in the gully bottom. Credit: K.G. Fisher

Fig. 10.45. Weaving juniper branches into a picket baffle. Credit: D. Muirhead

Around 2009, the Rio Puerco Alliance, led by Barbara Johnson, worked with the BLM and New Mexico Environment Department (NMED) to plan, fund, and construct several major restoration projects that built on what the volunteers had accomplished.

Bill divided seven miles (11 km) of the canyon and its tributaries into nine stream reaches, designing different treatment prescriptions for each reach. He then oversaw the implementation of these treatments while Matt Shultz of NMED assisted with planning, design, and pretreatment photos; Steve Vrooman of Keystone Restoration Ecology performed pretreatment monitoring; Steve Carson of Rangeland Hands, Inc. implemented the treatments; and Craig Sponholtz of Watershed Artisans built many of the restoration structures.

One major project involved realigning sections of the road through the canyon in order to promote wetland recovery, reduce wildlife disturbance, and improve access. Bill and Gene aligned the road to remove it from sensitive wetland areas, and the BLM designed and constructed it with federal stimulus funding. In one

place, a large rolling dip was installed to return flows that had been captured by the road to their original channel, rewetting about four acres of former wetland.

Bill also designed and oversaw a project to plug a large abandoned irrigation ditch above Cebolla Spring and return about 2,500 feet (762 m) of Cebolla Creek to its original channel. This filled in a depression that had been nicknamed "Lake Cebolla" because it captured water during the monsoons, but it also raised the bed of the channel about two feet and enabled riparian recovery in that reach.

Finally, Bill designed and supervised the construction of a "plug and spread" treatment in a major tributary canyon that successfully rewetted another 12 acres (4.8 ha) of former wetland that had been drained by an old irrigation ditch.

Although these large projects were built by professional contractors working with machines, volunteer labor played a critical role in making them possible (figs. 10.46A, B). They were funded by over $400,000 in state (NMED) and federal (U.S. Environmental Protection Agency) grants, and volunteer labor from groups including AWF, Talking Talons, and the National Wild Turkey Federation provided the required match for all of these grants.

Fig. 10.46A. A cluster of headcuts moving up the canyon, September 2011. Credit: M. Schultz

Fig. 10.46B. A large, machine-built Zuni bowl arrests the headcuts and helps retain moisture in the upper meadow. Credit: M. Schultz

In addition, because much of Cebolla Canyon is designated as wilderness, there are areas where machines are not permitted and the only option for implementing restoration structures is to have volunteers build them by hand.

The Transformation Begins

Since AWF began working at Cebolla Canyon, we have seen the wetland around Cebolla Spring grow from 7 acres (2.8 ha) to over 40 acres (16 ha), and scattered wetlands return upstream and downstream of the spring (fig. 10.47). With the wetland vegetation has come a noticeable increase in wetland animal species, particularly migratory birds like the Sora Rail.

The one-rock dams and burrito dams have filled in the shallow gullies in the uppermost meadows, and as of 2014 water now flows across the entire meadow in storm events, just as it did a century ago. Through one quarter-mile (0.4 km) section of the canyon, the channel has been reconnected with its former floodplain, stretching about 350 feet (106 m) wide. The juniper trees that had

invaded the meadows are beginning to die off as the water table rises, and sedges and bulrushes are returning to the wettest areas.

Downstream, there are many more perennial pools, areas where rock restoration structures are keeping the streambed wet most of the year (figs. 10.46A,B). We have found salamanders in some of those pools, and there are thriving patches of willows and bulrushes in the wettest corners of the canyon.

Throughout Cebolla Canyon, the gully downcutting and headcuts have nearly all been halted—and some are beginning to reverse themselves, collecting sediment and raising channel beds rather than lowering them with each major flow event.

As Bill explains, an ecological system tends to be either degrading or aggrading—either unzipping as water and soil and species are pulled away, or zipping back up again as the system returns to health and species diversity improves (fig. 10.47). Throughout much of Cebolla Canyon, we can see that we have flipped the switch, and a system that was degrading and downcutting is now collecting sediment, holding water, and nurturing wetland plant species that were formerly missing or scarce.

Fig. 10.47. Year by year the wetland is expanding down Cebolla Canyon.

Looking Ahead

As the wetland continues to expand, one hope is that we might be able to slowly reintroduce some of the animal species that died out when the wetlands vanished. (AWF assisted with the relocation of two nuisance beavers from Zuni Pueblo to Cebolla Canyon in 2005 (box 10.4), but unfortunately they only survived a few years.) Animal species that might someday return to Cebolla include muskrats (which create open ponds for waterfowl), voles and meadow mice (which dig tunnels that disperse water, as well as becoming food for raptors), leopard and western chorus frogs, and even small fish for the perennial pools that are beginning to reappear. Adding these species would amplify the restoration work that has already been done and bring Cebolla Canyon closer to the species diversity it once supported.

The great work of restoring Cebolla Canyon is only beginning. Bill has remarked that it took 70 years for Cebolla Canyon to degrade to the state we found it in 2000, and it will take another 70 years before it fully returns to a healthy, resilient, diverse state. Yet the changes are beginning to happen before our eyes, and in our lifetimes we expect to see many more acres of wetland and wet meadows return to life, creating habitat for animal species once native to this landscape.

Contact the Albuquerque Wildlife Federation to join the volunteer effort in Cebolla Canyon, and inspire similar efforts elsewhere.

Kristina Fisher is the Vice-President and Michael Scialdone is the President of the Albuquerque Wildlife Federation.

CHAPTER 11

Vegetation

The Forests are the mothers of the rivers.

—Plaque beneath the Save Our Trees statue at Brand Library in Glendale, CA, honoring the connection between the health of our water and the living watersheds that cleanse, moderate, and recharge its flow.

WHAT ROLE DOES VEGETATION PLAY IN WATER HARVESTING?

Vegetation is the key component of all water-harvesting earthworks. When vegetation is not present in a watershed, stormwater can become a destructive liability, flowing erosively away or pooling to breed mosquitoes before evaporating. In contrast, vegetation is a spongy living welcome mat that induces rain to quickly infiltrate into soil. Vegetation turns storm-water into a productive resource that irrigates plants for free, supports springs and creeks, and assists in groundwater recharge.

Vegetation brings water-harvesting earthworks to life. Plants anchor, build, and shelter soil—reducing erosion and controlling dust. Plants create the beneficial microclimates that support soil microorganisms and even more plant life. Vegetation provides wildlife habitat, food, fiber, livestock forage, building materials, medicine, oxygen, water-storage capacity, beauty, and more (fig. 11.1). Plants are *living pumps* that access and draw soil water up into fruits and seeds. We in turn eat this water in the form of a peach, pomegranate, olive, or mesquite pod. We are cooled by the water released from shade trees, which can reduce summer temperatures by as much as 20˚F (11˚C) beneath their canopies.[1] We enjoy water in the beauty of flowers, and the hummingbirds and butterflies they attract. The plant-based web of life— with the benefits it creates and the resources it generates

—steadily matures into greater size, productivity, and diversity. This living web is the regenerative element of the system (see box 1.1, chapter 1).

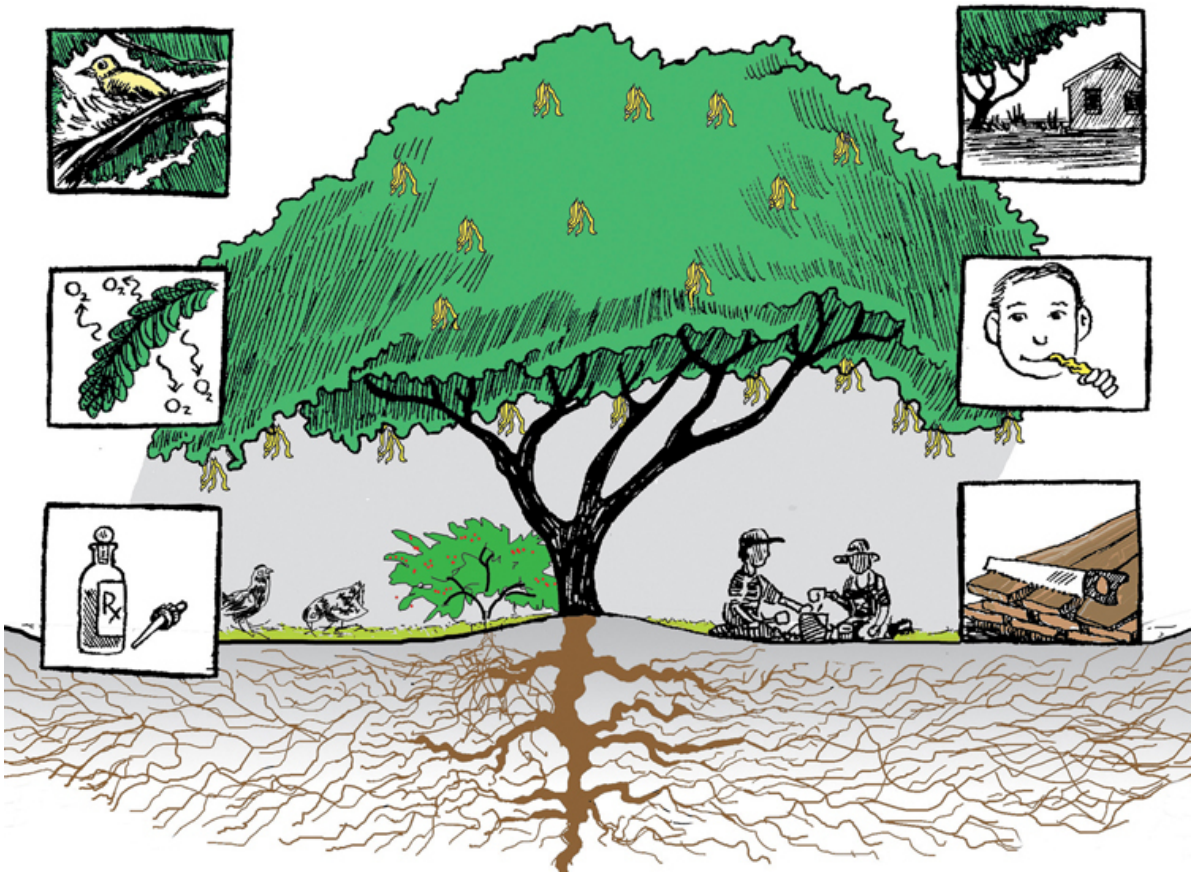


Fig. 11.1. A tree selected and placed to provide multiple resources

A water-harvesting earthwork without associated vegetation is dead. It can quickly erode, clog with silt, breed mosquitos, and excessively evaporate water. The addition of vegetation turns a dead system into a living system because it creates the conditions to sustainably support more abundant life than would otherwise appear. Roots expand, canopies grow, leaves fall and collect, and earthworms burrow, dramatically increasing the water-holding capacity and infiltration rate of earthworks while checking erosion. Insect-eating birds are lured in to provide nutrient-rich droppings, outside seeds, and mosquito control. Plants also harvest fog and create their own rain (search "Fog Harvesting" at HarvestingRainwater.com). Cleaner air and cleaner more abundant water are products of these enlivened systems.

In this chapter I encourage the liberal use of trees because the coverage and shelter of their canopies, and the extension of their soil-stabilizing roots, far

exceeds their comparatively small footprint on the ground (their trunk). A tree can provide plenty of space beneath its branches for gathering, planting, and playing. Shrubs, herbs, vines, and tubers grow as understory beneath and between the trees. And dense native grasses, sedges, and rushes work exceptionally well to cover and build soil.

Select vegetation appropriate to your site by getting to know the native vegetation in your area. Take a hike in undisturbed, nonirrigated natural areas. Better yet, take many hikes. Observe the native plants growing in a range of microclimates (moist depressions, hot dry slopes, canyons, and many others). Replicate these patterns at home by understanding existing microclimates, creating new ones, and planting appropriately. Trees can be planted within or beside earthworks. Shrubs, grasses, and groundcover are placed beneath or outside the shelter of tree canopies depending on their micro-climate preferences. Cacti and succulents typically prefer well-drained areas of the landscape.

WHERE IS VEGETATION USED?

Vegetation is planted within or beside every water-harvesting earthwork throughout all watersheds. Maximize vegetation's potential and functions using integrated design patterns detailed in chapter 4 of Volume 1, and using additional tips in this chapter. Follow these patterns to maximize the beneficial functions of plants as they guide you to thoughtfully select and place them in complimentary relationships with other site elements. For example:

- Enhance community by planting trees that beautify and shade natural gathering areas such as community mailbox clusters, post offices, playgrounds, bus stops, schools, libraries, and sidewalks/benches outside cafes (fig 11.2B). Shade invites folks to linger, talk, joke, and connect, while reducing exposed hardscape that creates the withering heat-island effect. Harvest runoff from the hardscape to support the adjacent plantings as discussed in chapter 8.

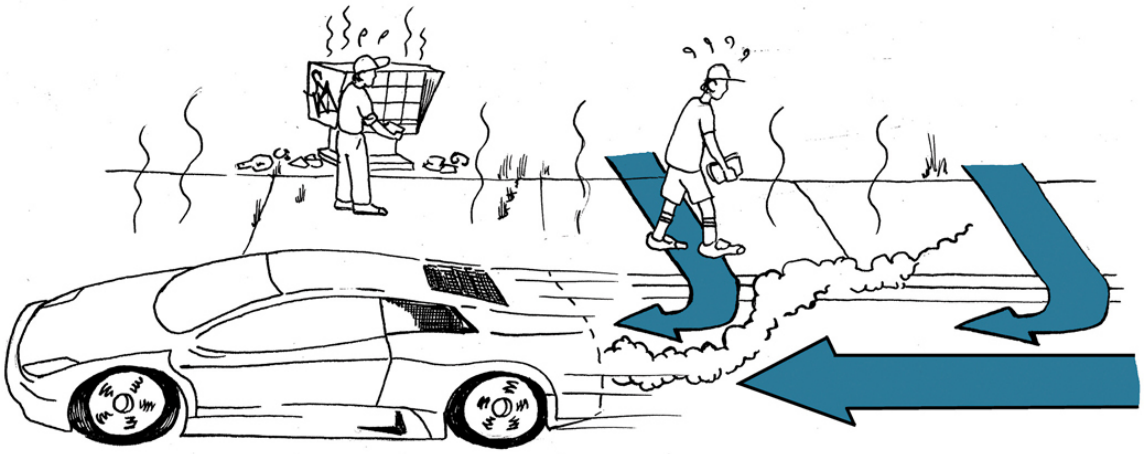


Fig. 11.2A. A hot, bleak environment that hinders community interaction due to its uncomfortable exposure

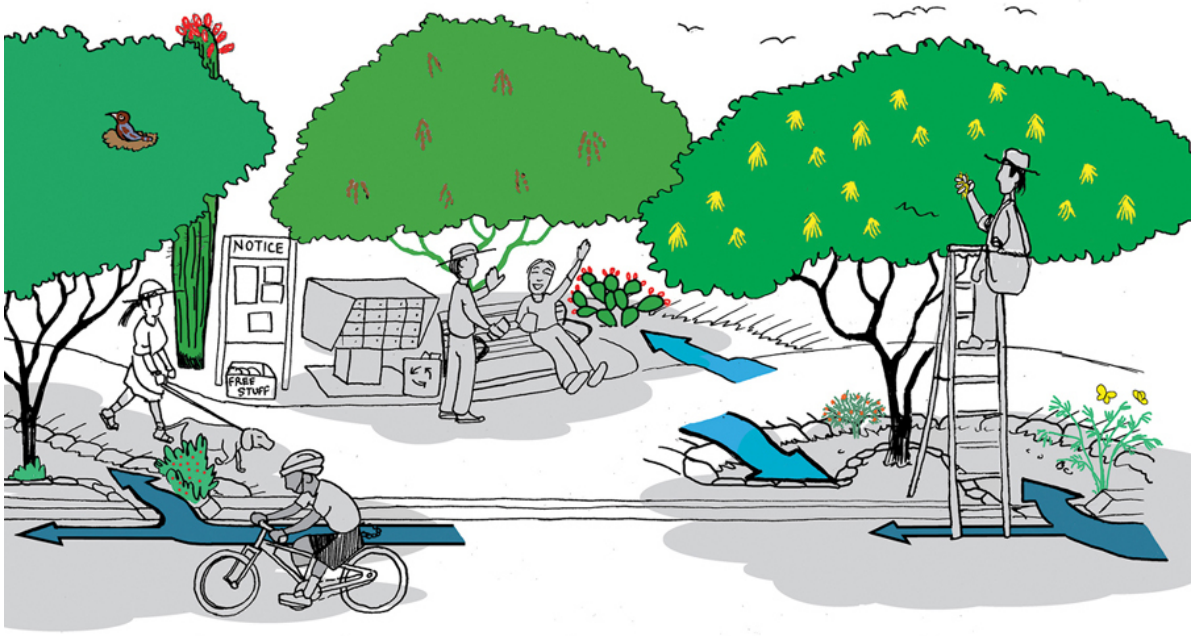


Fig. 11.2B. A sheltered environment inviting community interaction due to its comfort, life, and beauty

- Extend, enhance, and soften fences and walls with perimeter plantings. Newly planted vegetation located next to fences and walls is at reduced risk of being ru over or weeded out. As perimeter plantings grow, they can shelter added plantir tucked below. See fig. 2.13 for a small-yard example.

- Grow food-producing plants within easy reach of site water sources and the peo who will pick and eat the produce. This plant placement enhances local food security, improves health with fresh food, and results in better care for the plant

STEPS TO VEGETATE AN AREA

SITING PLANTS AND EARTHWORKS

Zimbabwean water harvester Mr. Zephaniah Phiri Maseko, whose simple earthworks and watershed management has turned wastelands into oases, once said, "The land must harvest water to give to the trees, so before you plant trees you must plant water." Start work at your site by creating water-harvesting earthworks to plant water within the soil. *Then* plant trees and other vegetation within or beside these earthworks.

Siting plants and earthworks by zones of available resources

Focus initial earthwork construction within your site's oasis zones where rainwater runoff and greywater are concentrated, and where you—the site steward — spend much of your time (chapter 1, water harvesting tip number 5; and chapter 12, site considerations section). This will increase the speed of revegetation, and provide the maximum benefits in the location where you spend the bulk of your time—right around your home, in gathering and activity areas, and along well-used paths. Oasis zones can have dense, diverse mini-forests of exotic/native food plants, or just more robust native plantings than the less water-rich zones of your site can support. It all depends on what you and your water supply can sustainably support.

Selecting plants according to their comfort range

Select vegetation well-suited to the climate and soils of your site so plants will naturally and passively thrive without imported water and nutrients, or excessive time and labor to make up for what the plants lack. Get to know your area's native vegetation through observation and through books on regional ecology, plants,

and gardening. Talking with local gardeners, native plant enthusiasts, and locally owned plant nursery staff can help in identifying suitable plants and learning about their preferences. In this chapter, see subsections on "Perennial Native Plants," "Selecting Plants to Keep Their Water Needs Within the Bounds of On-Site Water," and box 11.2 later.

Select herbs, vegetables, fruit trees, and nut trees well-suited to your climate. Citrus thrive best in warm to hot, frost-free climates, while apples are generally better-suited for cool climates with average temperatures of 65° to 75°F (19° to 24°C).[2] Focus on cultivars or varieties appropriate for your specific locality and soils that have flavors and textures you prefer. Cultivars are varieties of domesticated plants cultivated for adaptation to specific soil types, climate extremes, local pests, or with preferred flavors, colors, fragrance, texture, and fruiting times. Cultivars are typically created by farmers and gardeners through careful selection, seed saving, and grafting of plant stock from their favored specimens. Well-adapted varieties or cultivars will thrive and produce an abundance of fruit in your climate and soils, while those better-suited to other climates and soil types will suffer and produce little to nothing at your site. For example, heat-adapted Anna and Ein Shemer apple varieties do well in my low desert region. Empire and McIntosh apple varieties do well in cooler climates. See appendix 4.

Selecting sites and microclimates for plants' comfort range

Select the plant types and cultivars best suited at your site, and place them in their preferred microclimates.

SOLAR ORIENTATION

Plant heat-tolerant and heat-loving plants in hotter microclimates on the west-facing and winter-sun sides (south-/equator-facing side in northern hemisphere, or the north-/equator-facing side in southern hemisphere) of hillsides, buildings, fences, and other vegetation. Plant cold-tolerant and cold-loving vegetation on the colder winter-shade side (north-facing side in the northern hemisphere, or south-facing side in southern hemisphere, fig. 11.3).

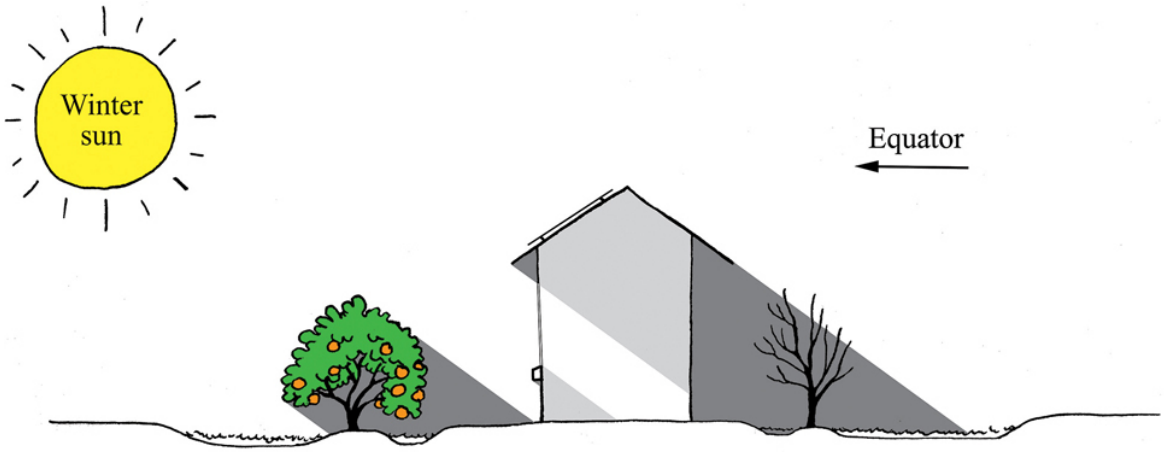


Fig. 11.3. Planting for cold and warmth needs. A cold-sensitive evergreen citrus tree on the warm winter-sun side of house, and a cold-needy winter deciduous fruit tree on the cold winter-shade side of house. Note: Citrus tree is placed so it will not shade winter-sunfacing windows of house in winter.

Many deciduous fruiting plants have a *chilling* requirement of 100 to 1,000 hours of temperatures below 45°F (7°C) to break their winter rest period.[3] Without sufficient cold, buds won't open or will open unevenly in the spring. Blossom buds often require less cold than leaf buds, so in temperate latitudes blossom buds frequently open before leaf buds begin to grow. Fruit may fail to set if leaves do not develop soon enough to provide food shortly after the blossoms open. In my warm climate, I place such plants in colder microclimates with more winter shade to help get the needed chill. Placement in colder microclimates also reduces the chance of fruit trees warming up and flowering too early in the spring, resulting in late frosts killing off early blooms (fig. 11.3). Using late-blooming varieties also helps avoid spring frost damage. Receiving less solar heating also aids in maintaining higher soil moisture since water loss to evaporation and evapotranspiration increases with a rise in temperature.

Citrus trees and vegetable gardens don't like either cold or excessive heat, so in my region I place them in warm east-facing and winter-sun facing locations, while avoiding hotter west-facing exposures. In cooler regions, west-facing exposures for citrus trees and gardens may be fine.

WIND

Wind increases water lost to evaporation and evapotranspiration, intensifies cold, and can break limbs, damage fruit, and carry fire. But wind can also cool in

summer or provide renewable energy through wind power. Research and observe how prevailing winds change through the seasons in both force and direction at your site and in your region. At your site, use screening strategies to deflect or divert unwanted wind, or to harvest wind that is useful (figs 11.4, 11.5). Porous windbreaks are preferable to solid windbreaks and barriers (e.g. walls and buildings), which induce destructive turbulence as the wind tumbles, swirls, and continues over and around them. Porous windbreaks such as latticed fencing, trellised vines, and tough native shrubs and trees *slow* wind rather then blocking it completely. In wet climates, porous windbreaks also allow good ventilation to help prevent mildew.[4] Evergreens fare best as winter-wind windbreaks since they don't drop their leaves. Search "Wind & Snow Harvesting" at HarvestingRainwater.com for more.

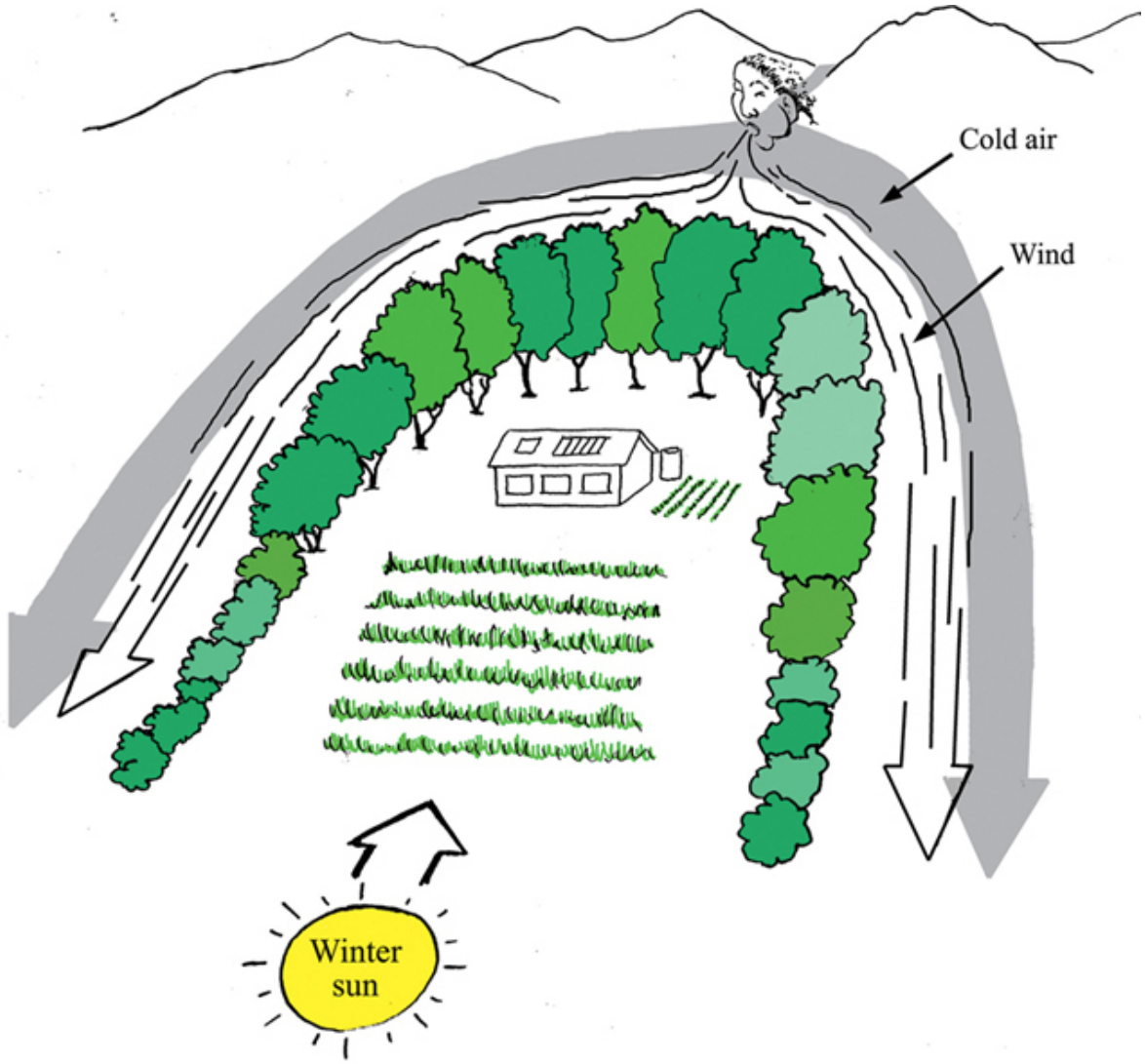


Fig. 11.4. A solar arc and windbreak of trees and shrubs harvesting winter sun, while diverting and deflecting cold winter winds and cold air drainage around a home

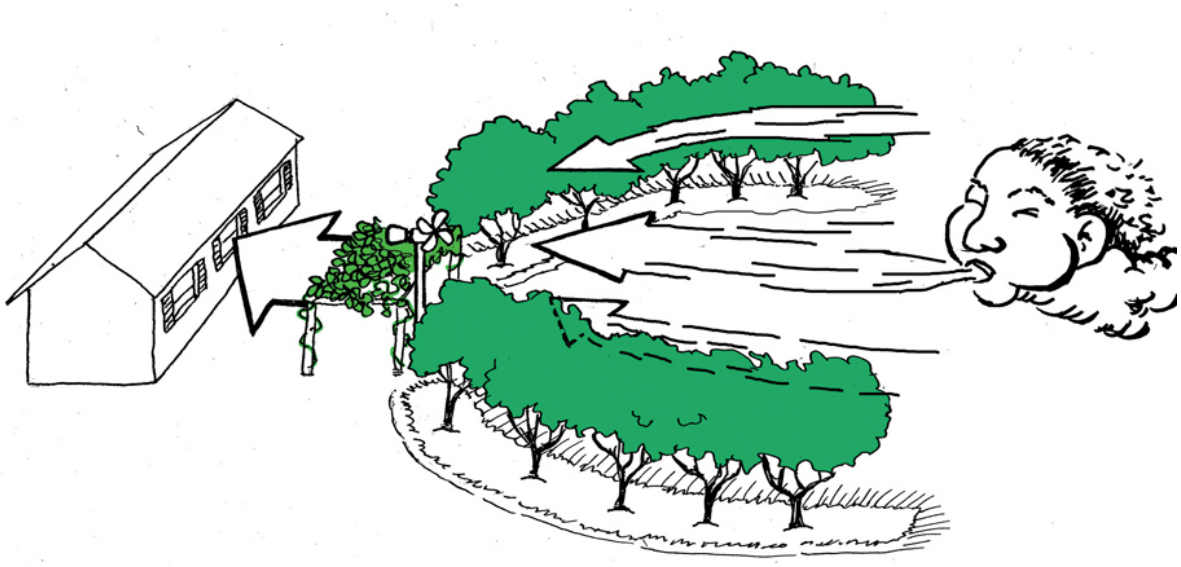


Fig. 11.5. A wind harvester of trees and shrubs directing and concentrating wind toward a house for passive cooling and wind power. Adapted from *The Solar House: Passive Heating and Cooling* by Daniel D. Chiras, Chelsea Green Publishing, 2002

COLD AIR

Cold air flows downhill like syrup, often damming up behind obstacles and pooling in low spots. Place cold-tender plants on slopes or place them beside—not within—basins in flat yards, so plants do not sit in the low spots where cold air pools. If cold air pools behind a solid fence or wall where you don't want it, a section of permeable wire fencing or an open gate can drain it away. Frost-free *thermal belts* are often located at least 100 feet (30 m) above the nearest low ground or valley bottom, and below colder high elevations. To avoid frost damage, hillside planting strategies might consist of placing early-blooming varieties in the thermal belt near the top of a hill where cold air will quickly drain past them, and late-blooming varieties at the bottom of the hill.

Plantings can deflect or harvest cold air. An arc of vegetation placed upslope of buildings, gathering areas, and gardens, with the ends of the arc facing downward deflects cold air around these sites (fig. 11.4). An arc of vegetation placed just downslope of these sites, with the ends of the arc facing upwards harvests the cold.

A screen of tall, dense vegetation placed on the downslope bank of a pond will retain the evening's cold air and cool water temperature, thus reducing water lost to evaporation—which increases as temperature increases. See appendix 4 for more resources on microclimate assessment.

Trees and Other Vegetation

Begin with trees. Trees are the pillars of the vegetative framework of your landscape. Play with an array of potential locations for trees and earthworks. Mark potential locations on the ground by scuffing lines in the dirt representing the full diameter of the mature canopy of each tree placed beside the water-harvesting earthwork supporting it (fig. 11.6A, B). Now sit outside with a tall glass of iced tea and imagine what things would look and feel like with *full-grown* trees in the areas you marked. Walk around these imaginary trees. If you plan for any size less than the trees' eventual full sizes, you will waste time and money planting too many trees, too close together. Make sure there are no conflicts with overhead or underground utility lines. Make sure trees will not shade out solar panels, solar water heaters, winter gardens, or winter-sun-facing windows (see figs. 11.7A, B, C, D for examples). Determine the longest shadow a mature tree or other object will cast on the winter solstice (December 21 in the northern hemisphere, June 21 in the southern) by looking up your latitude in box 11.1 and multiplying the tree's height by the associated factor of the shadow ratio (fig. 11.7C).

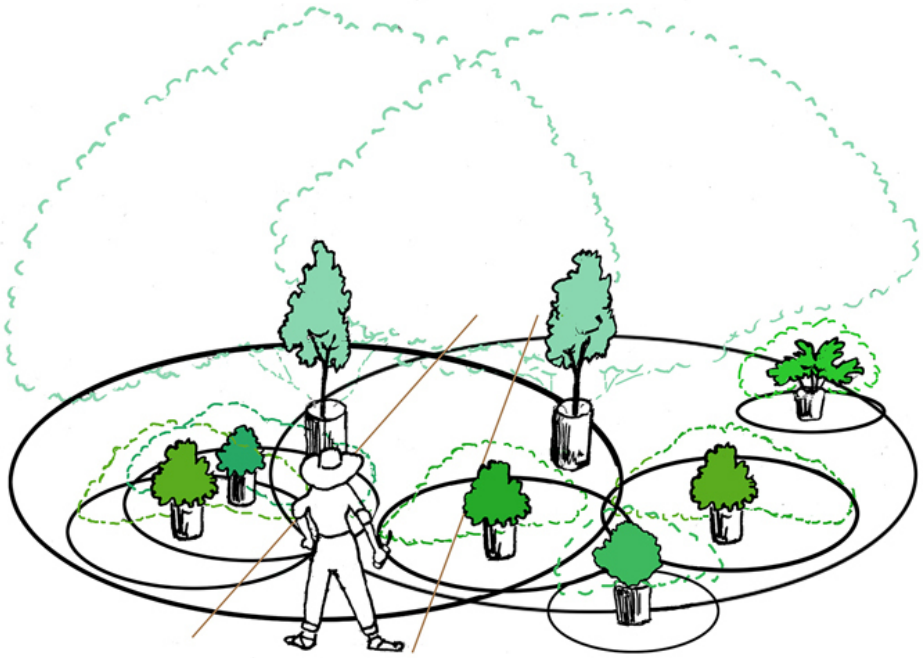


Fig. 11.6A. Young plants from plant nursery placed too close together as illustrated by circles drawn in dirt to represent the new plants' expected size at *maturity*. If planted as is, they will grow to crowd one another and block the pathway.
Move and reassess the plants' placement as needed.

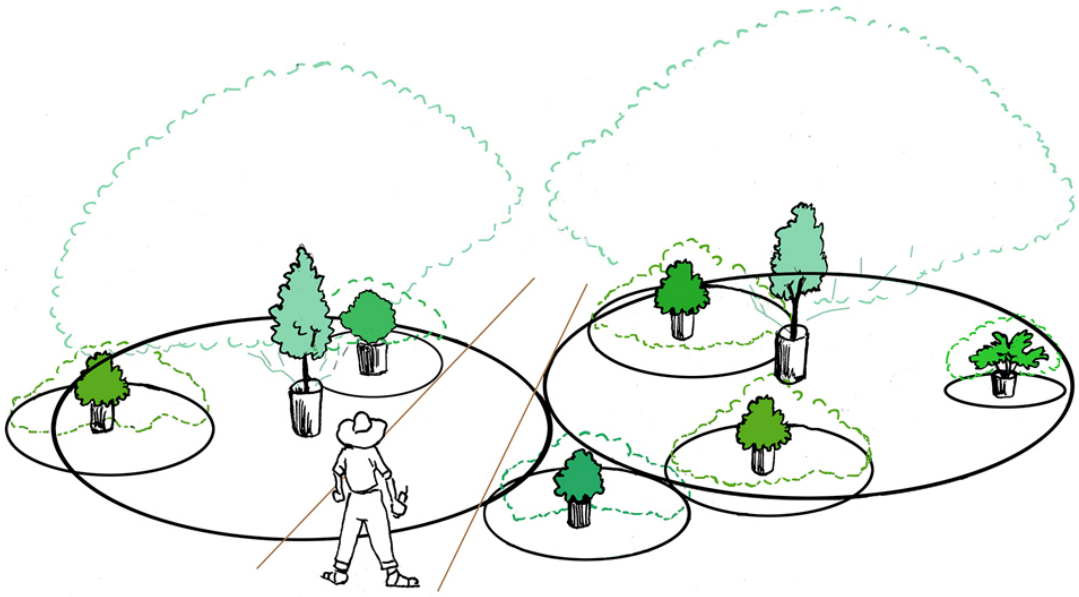


Fig. 11.6B. Plants well-placed and spaced based on their expected mature size. No future crowding or blocking of pathway. The plants can now be planted.

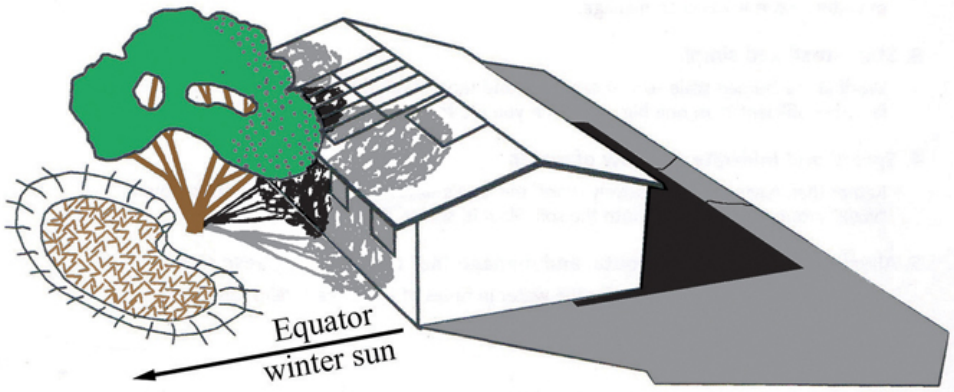


Fig. 11.7A. Majority of winter solar access lost due to a misplaced evergreen tree. At 32° latitude from 9 A.M. to 3 P.M. on the winter solstice, the tree blocks winter sun exposure for winter-sun/equator-facing windows and rooftop solar water heater and solar panels. Shadows are shown as gray for 9 A.M. and 3 P.M. Solar noon shadows are black.
See box 11.1 and Volume 1, 2nd edition, chapter 4 for simple ratios and calculation information to determine winter shadow lengths and sun angles throughout the year for better placement of shadow-casting trees and structures.

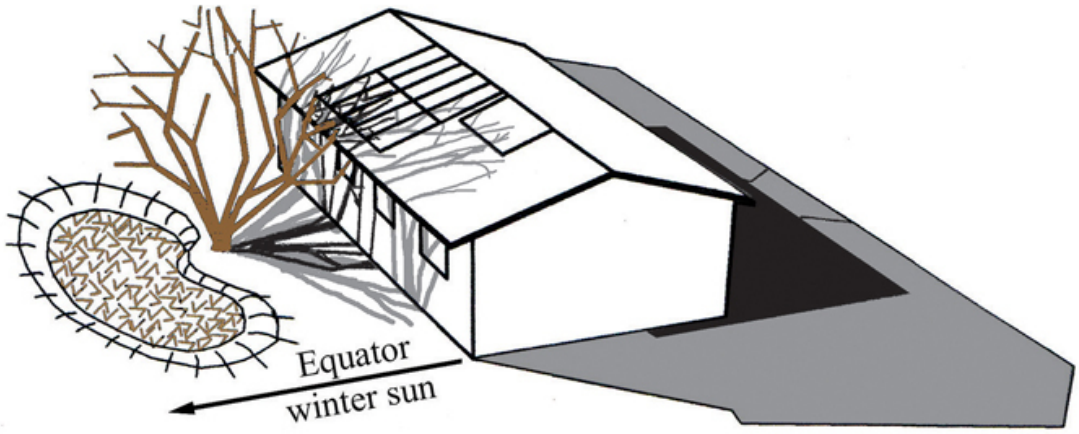


Fig. 11.7B. Over half of winter solar access lost due to a misplaced deciduous tree. At 32° latitude from 9 A.M. to 3 P.M. on the winter solstice, the bare branches of the tree shade out over 50% of winter sun exposure, increasing heating costs and severely hampering solar power production.

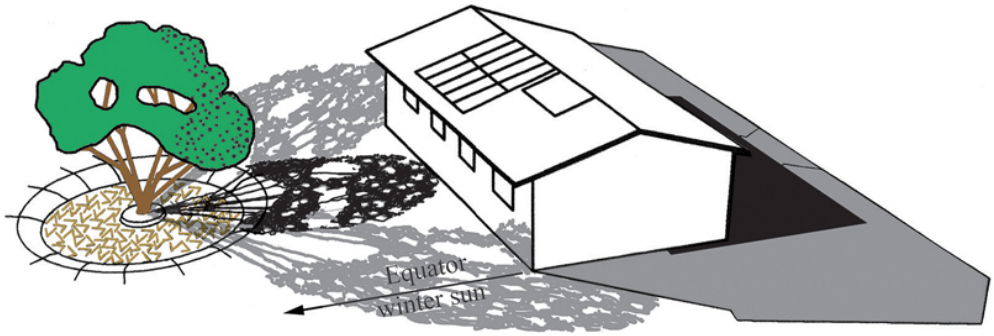


Fig. 11.7C. Winter solar access retained. At 32° latitude from 9 A.M. to 3 P.M. on the winter solstice, an evergreen tree planted sufficiently far from the house, so solar access is retained from the bottom of the winter-sun/equator-facing windows up through the equator-facing slope of the roof.

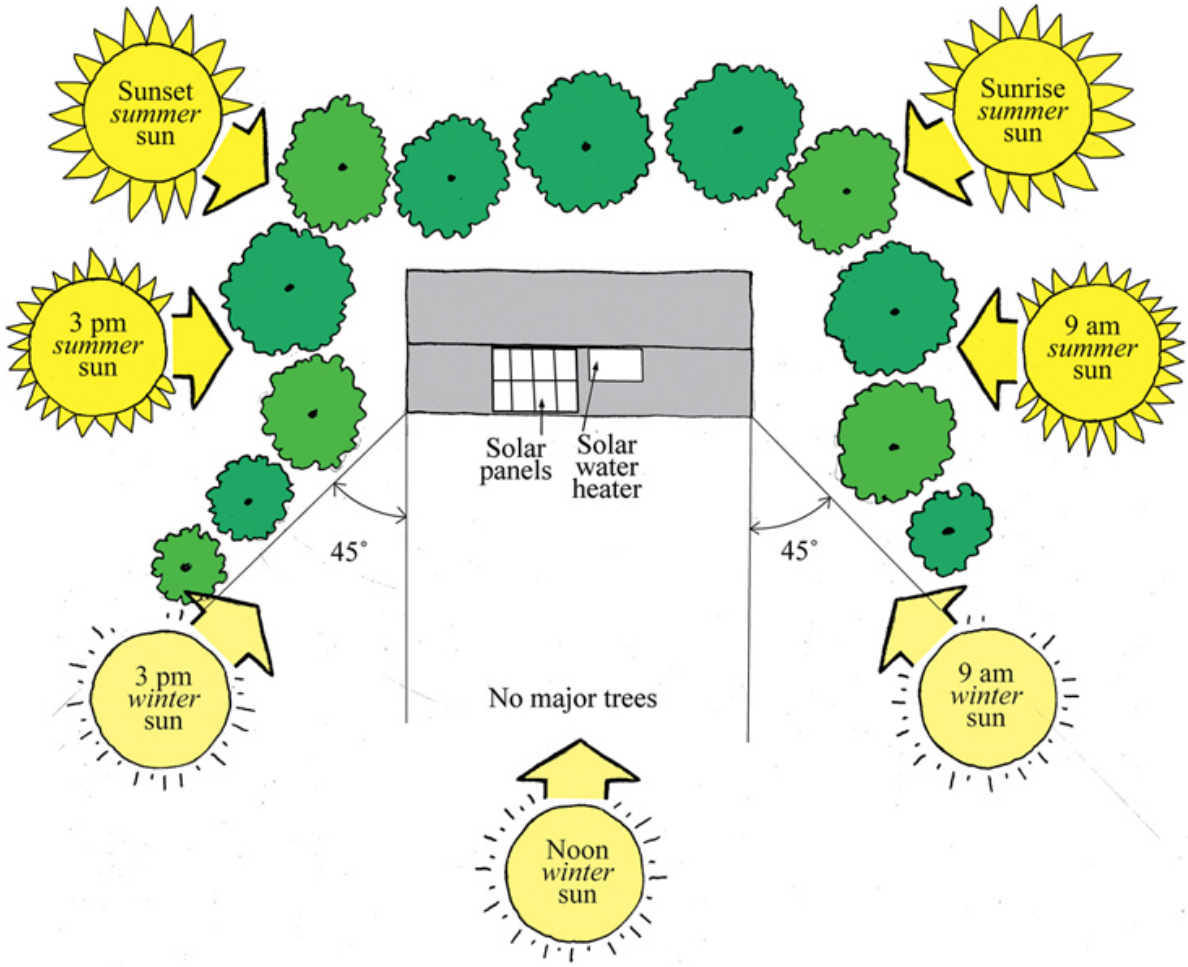


Fig. 11.7D. Trees planted only outside the area marked "no major trees" to retain winter solar gain for winter-sun facing windows, solar panels, and solar water heater. Winter-deciduous trees planted on the east and west sides of building shade out rising and setting sun in hot months, while letting in some light and heat in winter. Evergreen trees planted on winter-shade-side of house (north-facing in northern hemisphere, south-facing in southern hemisphere) further shade home from rising and setting summer sun. Adapted from *Designing and Maintaining Your Edible Landscape Naturally* by Robert Kourik, Metamorphic Press, 1986.

Box 11.1. Noontime Winter-Solstice Shadow Ratios

Use the ratio 1:x to get the *length* of the shadow cast by an object (tree, cistern, house) for each foot (or meter) of height. Multiplying the height of the object times x tells you the length of the shadow in feet (or meters) at noon on the day with the longest shadows of the year.

North or South Latitude	Object Height: Length of Shadow Cast at Noon
0°	1: 0.43

4°	1: 0.52
8°	1: 0.61
12°	1: 0.71
16°	1: 0.82
20°	1: 0.95
24°	1: 1.09
28°	1: 1.25
32°	1: 1.45
36°	1: 1.69
40°	1: 2.00
44°	1: 2.41
48°	1: 2.98
52°	1: 3.85
56°	1: 5.36
60°	1: 8.70
64°	1: 22.37
66.56° and higher (Arctic/Antarctic), sun never shines on winter solstice	

For ratios for every degree of latitude, search "Winter-Solstice Shadow Ratio & Azimuth Table" at SunAndShadeHarvesting.com

If your imaginary placement has trees too close together or in the wrong spot, move your marks and imagine the new design. Determine how rainfall runoff and greywater could be directed to the earthworks supporting the trees. Make room among the trees for gradually meandering raised pathways and gathering and play areas. Keep playing with your tree layout until you find the optimal design for your site.

Perennial Native Plants

Perennial drought-tolerant native plants can be placed anywhere at your site. As true local survivors, these plants are the best choice for areas distant from convenient human access, household runoff, and grey-water. Perennial plants act as long-lived anchors in the landscape. They grow extensive root systems to access soil moisture in dry seasons and drought years. I define native plants as vegetation indigenous to a 25-mile (40-km) radius of a site, found within 500 feet (150 m) of the site's elevation, and in a similar microclimate to that of the site's. So if you have a dry site, a high-water-use cottonwood (*Populus* spp.) tree found along a perennially flowing creek 20 miles (32 km) away wouldn't really be native to your site's dry conditions. But a lower-water-use acacia (*Acacia* spp.) tree found growing along an ephemeral arroyo 20 miles (32 km) away would be native to your site's

conditions—especially in a spot receiving additional seasonal roof or road runoff (box 11.2).

Box 11.2. Tracking and Restoring Native Plants in a Disturbed Urban or Suburban Core

Finding native plants in built-up areas is becoming more challenging as "development" covers more land. But look closely and you will find pockets of undisturbed land and vacant lots that have never been bladed. Walk these sites with good native plant identification books and observe everything up close. To see bigger swaths of intact native ecosystems you may need to look within a 50- or a 100-mile (80- to 160-km) radius of your site. Track down historic native plant lists from university herbariums or local native plant societies. Purchase native plants that naturally grow near your site, or that historically grew there. These are the species best adapted to the local subtleties of your site's climate and soils. You can collect seed to grow out plants yourself, or contract with a nursery to grow them for you, but do not collect wild plants.

Then bring the natives back! Plant them in yards and neighborhoods in the urban and suburban core. As the native plants grow, native birds will follow and carry seeds to new pockets in the city. The diversity of plants, nesting birds, and visiting butterflies in my inner-city yard and neighborhood has soared since we reintroduced native plants like the delicious-seeded foothills palo verde (*Parkinsonia microphyllum*), the edible-flowered, hummingbird-attracting chuparosa (*Justicia californica*), and the colorful pollinator–friendly snapdragon vine (*Maurandya antirrhiniflora*). I planted the living seed bank in my yard—the wind, water, and wildlife planted the neighborhood.

Some sites may require defining *native* with a larger radius to bring in more diversity, but start with the small radius to ensure you do not overlook superior local species. Native plants have spent millennia coevolving with local soils, climate, and wildlife so they require no fertilizers or pesticides, they support the greatest density and diversity of native wildlife, and they can live on natural rainfall alone. Native plants can be minimally pruned, but do not require it.

Perennial and annual climate-appropriate exotics

Although I promote the use of low-maintenance, low-water-use native plantings, I'm not against exotic plants. I love them if they meet three criteria:

- They are non-invasive
- Their water consumption does not contribute to exceeding the site's on-site wat budget
- They increase rather than deplete on-site resources. Climate-appropriate, food-bearing, exotic perennials are my favorite

Exotic plants typically need more water and care than low-water-use natives, especially if you want them to produce fruit (figs. 11.8, 11.10-11). If under-watered, some fruit trees may look fine but never produce fruit, and what's the point in that? Appropriate selection and placement of fruiting exotics is key. I place them in wetter oasis zones within 30 feet (9 m) of buildings to get more roof runoff, greywater, and care, which in turn increases production and success (see tip 5 in chapter 1 and illustrations in chapter 12). More drought-tolerant exotics can be placed in drier oasis zones that lack greywater.

Fig. 11.8. A section of a 60-foot (18-m)-long, 2.5-foot (0.75-m)-wide, 1.5-foot (0.45-m)-deep, two-tiered berm 'n basin full of rain at Occidental Arts and Ecology Center in northern California. In 2006, 96 inches (2,438 mm) of rain fell, resulting in this b'nb harvesting over 600,000 gallons (2,274,000 liters) of runoff. Most of the water comes from a 4-inch (100-mm)-diameter drain pipe from a diversion drain installed upslope to dewater a 1/3-acre (0.13-ha) area above a septic leach field. This pipe used to daylight onto a steep forested slope forming a gully 5 feet (1.5m) wide and 4 feet (1.2 m) deep, from which erosive sediment flowed down to contaminate a stream of spawning salmon. Now the gully has been stabilized, and the b'nb intercepts the runoff to help recharge groundwater while improving the stream's water quality for the salmon. Such b'nbs, typically with smaller catchments, are also used on the site to passively irrigate apple, apricot, peach, and plum trees. The trees are planted beside, but

not within, the basins, so the root crown is better drained in this wetter climate. Credit: Brock Dolman.

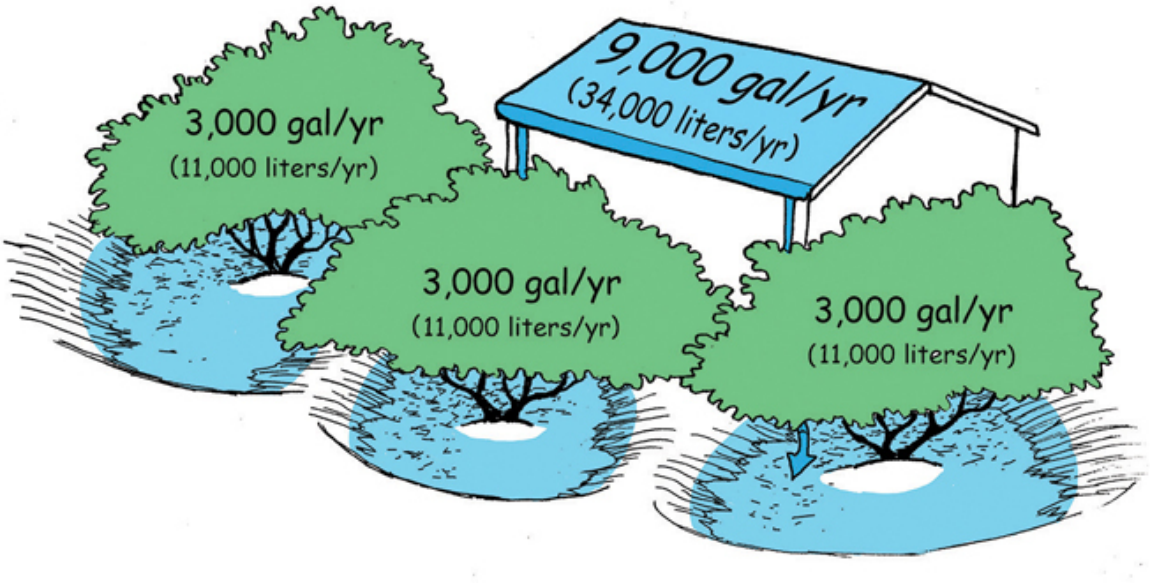


Fig. 11.9. Annual irrigation demand in Tucson, Arizona, of low-water-use, dry-season-adapted, native mesquite trees met by rainwater supply from roof runoff

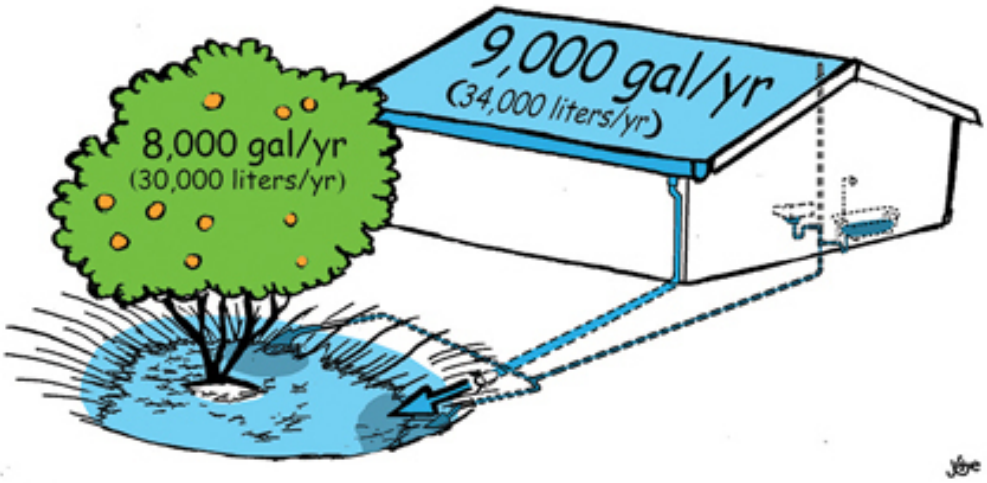


Fig. 11.10. Annual irrigation demand in Tucson, Arizona, of higher-water-use, dry-season-susceptible, exotic citrus tree met by rainwater supply from roof runoff, and supplemented with greywater in dry times

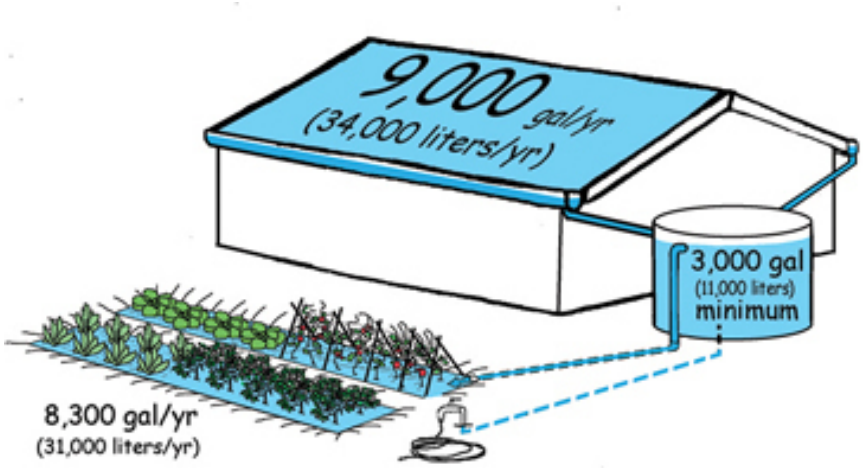


Fig. 11.11. Annual irrigation demand in Tucson, Arizona, of 130-ft^2 (12-m^2) high-water-use vegetable garden in sunken, mulched basins. Cistern needed to dole out roof runoff in long dry times

Pomegranates (*Punica granatum*), fruiting olives (*Olea europaea*), and cultivars of non-native edible fruiting cactus (*Opuntia ficus-indica*) have relatively low water needs. They do not thrive and produce on direct rainfall alone in my town (average 12 inches or 304 mm per year), but can flourish with additional rainfall runoff without added greywater. I planted these species beside basins in the public right-of-way in front of my house where harvested runoff from the street and footpath boosts their growth and fruit production. Move up about 1,000 feet (300 m) in elevation to the community of Oracle, Arizona, where additional rainfall (average 19 inches or 482 mm per year) and cooler north-facing microclimates increase the diversity of exotic food plants that can be grown on harvested rainfall and runoff to include grapes, apricots, peaches, and pistachios. (On average, temperatures drop about 3.5˚F or 2˚C with every 1,000-foot or 300-meter gain in elevation).[5] In other communities with wetter or cooler climates, apples, plums, walnuts, and more can produce solely on rain and runoff harvested in the soil.

To find appropriate multiuse perennial exotics for your area, seek out local abandoned orchards to see what plants are surviving without care. Seek out active orchards too—especially ones that are dry-farmed. Mimic the microclimates and cultivars too, if you like the fruit. If you can't find local cultivars in local plant nurseries, investigate mail-order sources or take cuttings from local trees and graft them to root stock to create your own nursery stock plants.

For exotic annuals such as vegetables choose *heirloom* or *open-pollinated* varieties. This way you can select, save, and replant seeds from your most healthy,

productive, tasty plants—creating new varieties or subspecies especially well-adapted to your climate, soils, tastes, resistance to local pests, and gardening style. Avoid hybrid and genetically modified (GMO) seed. As Suzanne Ashworth's great seed saving resource *Seed to Seed* states, "Standard [open-pollinated] varieties will come "true-to-type" (produce plants like their parents) if not allowed to cross with similar varieties growing nearby. In contrast, hybrids are the result of deliberately crossing two different parent varieties, usually inbreds. Hybrids should be avoided for seed-saving purposes, because they are incapable of producing plants like the previous generation. Seed saved from hybrids will either be sterile or will begin reverting to one of the parent varieties during succeeding generations."

Plant exotic annuals in the best seasons for your area. In lower latitudes cabbage, broccoli, cauliflower, onions, garlic, spinach, lettuce, chard, beets, and carrots prefer cool weather and will produce in winter or spring when supplemental-irrigation needs are lower than in hot summers. If you plant in locations convenient to the user, produce is much more likely to be used. Culinary herb gardens work great when placed just outside kitchen doors, if solar exposure in that location is appropriate.

For additional resources including books, organizations, nurseries, and seed catalogs see appendix 4.

Native grasses and annuals

Native annual grasses and wildflowers work great as rain-activated accents that flesh out perennial landscapes in years of good rain. Their seeds lay dormant in the soil in dry years. To establish them, roughen soil with a hard rake just before the rainy season, broadcast the seeds, and rake soil to cover so birds, rodents, and ants do not immediately eat them. Keep at least a 10-foot (3-m)-wide grass-free perimeter around buildings to reduce fire risk when the grass dries out.

Box 11.3. Planting for Wind-, Gravity-, and Water-Distribution of Seed

Use your observational skills to get natural forces to help you plant for free. This is particularly useful on large sites needing major revegetation, but can also be useful on small sites. Plant low-water-use natives where the seeds they produce will be carried naturally to needed germination sites. For example, observe the direction of seasonal prevailing winds and plant species that produce light, wind-blown seeds upwind of areas needing revegetation. Planting on high points and ridges can help broadcast seed farther. Plant species producing heavier seed high in the watershed where seed will flow downslope with runoff and gravity. In the urban environment, establish street-side plantings to distribute

seed via stormwater flowing in the street. Seeds from species planted along natural drainages can be carried both upslope and downslope along these transportation corridors by wildlife picking up seed in their coats, mouths, and guts. This service is enhanced when you plant species whose fruit is particularly relished by local wildlife.

SELECTING PLANTS TO KEEP THEIR WATER NEEDS WITHIN THE BOUNDS OF ON-SITE WATER

Strive to create a vibrant landscape that, once established, will be sustained by a hierarchy of water use where:

- Rainwater is the *primary* water source
- Greywater is the *secondary* water source
- Well or municipal water is a *supplemental* source used only during times of neec such as drought

With this water-use hierarchy you can create a beautiful landscape that produces more resources than it consumes and is in balance with your on-site rainwater budget. The supply side of this budget includes rain and snow falling directly on your site and "runon"—runoff running onto, and harvested within, your site from offsite sources. A landscape irrigated only with these water sources is sometimes called a *rain-only landscape* or a *precipitation-only landscape*.

Augment this water supply using your personal "wastewater" transformed into your personal "recycled resource" by properly distributing greywater from household drains (but not the toilet) to the landscape (see chapter 12). Such a landscape is sometimes called a *free-water landscape*, since the precipitation and runoff comes to you free of charge, and the gravity-fed distribution of the greywater to your plants and soil freely turns an on-site "waste" into an additional water resource.

Use the calculations shown in chapter 1, boxes 1.3 and 1.4, and figs. 1.20 and 1.21, to determine the supply side of the water budget for your site. See boxes 12.6, 12.8, and 12.9 in chapter 12 to estimate volumes of supplementary on-site greywater. Select potential plantings by adding their water needs and comparing that total to the total volume of water available on site. Then weigh the trade offs between the water demand of different species and your preference for the species you want at your site. For example, in southern Arizona a series of infiltration basins receiving 9,000 gallons (34,000 liters) of annual rainfall and runoff can

support three mature 20-foot (6-m)-tall, low-water-use native velvet mesquite trees, each needing about 3,000 gallons (11,300 liters) of water a year (fig. 11.9). This same amount of water can instead support one mature orange tree needing about 8,000 gallons (30,300 liters) of water a year (fig. 11.10).[6] Or this same amount of water can support a 130-square-foot (12-m^2) vegetable garden (fig. 11.11).[7]

However, the drought-sensitive citrus tree will require water from a cistern or household greywater to provide dry-season waterings, which low-wateruse native mesquites will not require. Delivering household greywater to the citrus tree boosts the volume and frequency of watering without increasing household water demand, and could prevent the need to install a cistern. To keep the water-thirsty garden healthy year round, it will need a large cistern to provide enough rainwater for dry-season waterings. Surface greywater irrigation is not recommended for lawns, in order to prevent those playing on lawns from coming into direct contact with the greywater. And while subsurface greywater irrigation of lawns is possible,[8] I typically don't recommend it either, due to the high costs and complexity of such a system irrigating thousands of tiny root systems throughout the lawn, rather than a cheaper, simpler system irrigating one large root system of a tree.

The water, soil, and microclimate conditions plants are exposed to vary from site to site in the same region, and vary even more between regions. You can get information about plant needs relevant to your area from local gardeners, local irrigation publications, plant books, agricultural cooperative extension agencies, and (in Arizona) the Arizona Department of Water Resources' *Low Water Use/Drought Tolerant Plant List*. (See the resources in appendix 4 for plant list sources.)

But the most fun way to learn about plant needs is to TAKE A HIKE! Estimate the needs of plants by observing the natural conditions under which they grow *without irrigation*. Walk wild areas where seeds sprout and grow to maturity on rainfall alone. Walk feral areas like abandoned orchards and once-nurtured landscapes that are now supported solely by rain. Get to know local species using good plant identification books and taking walks with enthusiastic plant experts. Look around and ask yourself: What lives? What dies? What thrives? What struggles? Where? Why? And at what densities?

Drought-tolerant plants grow in exposed areas where they survive on the rain that falls directly on them. More water-needy plants are found along drain-ages, waterways, and roadside ditches where runoff is concentrated. Plants you find

growing in depressions ought to grow in infiltration basins. Plants you find growing in drainages should do well near one-rock dams. Observe plant species naturally growing near one another. Which plants like full sun? Which grow under a canopy of shade? What planting densities can be naturally sustained? What excessive planting densities with excessive water needs lead to plant stress and death? Mimic what you observe working in the natural environment when you select species and decide their planting locations at your own site. If your site is on a well-drained, dry, south-facing slope, look for examples of wild vegetation growing on similar slopes. Replicate this native plant palette and plant distribution pattern on your land. You should have success as long as you do not try to replicate plant palettes and patterns growing in microclimates very different from your own. However, you can introduce plants from a slightly wetter microclimate if you first create a wetter microclimate by converting a landscape that drains water into one that harvests water.

When planting water-harvesting earthworks or rain gardens, place vegetation in its ideal *rain garden zone*. There are three *rain-garden zones*, each for a different microclimate within or beside a rain garden (figs 11.12A - E):

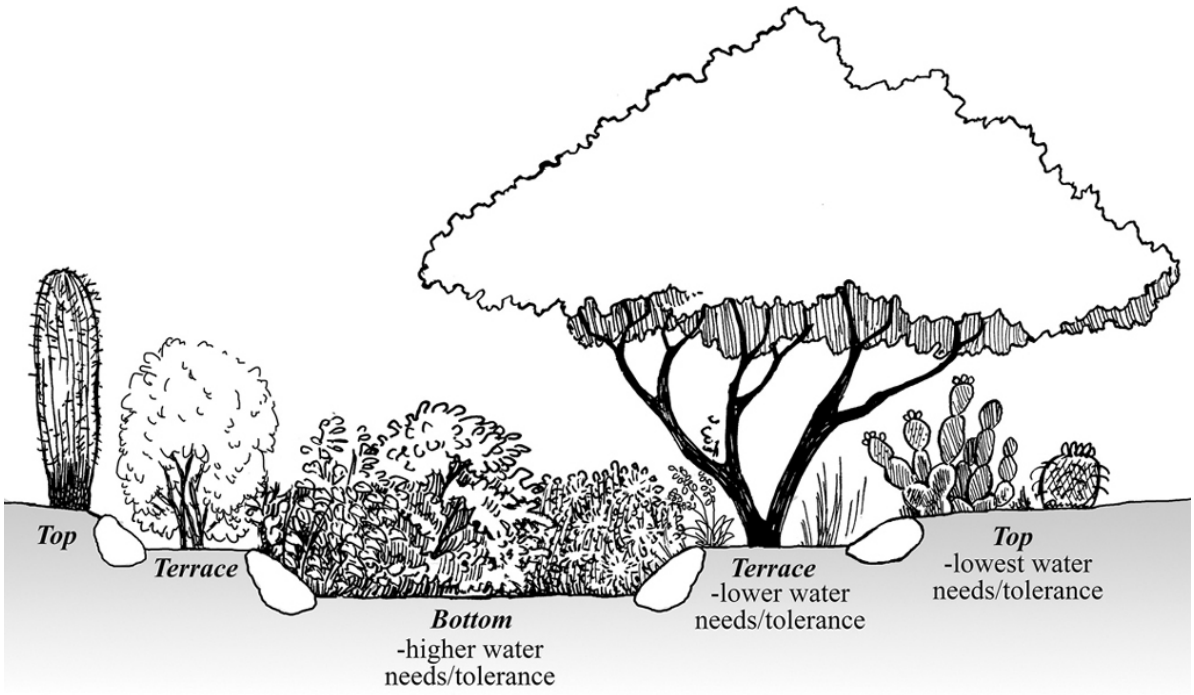


Fig. 11.12A. Plants' water needs and tolerances determine their ideal Rain-Garden Zones

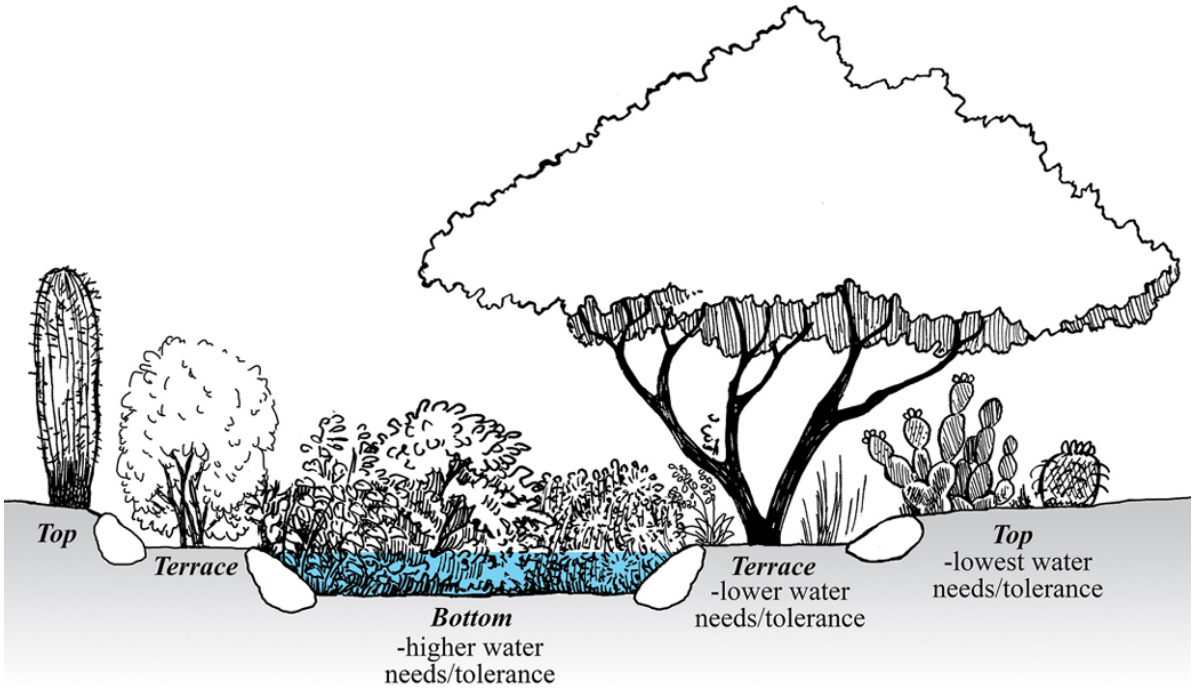


Fig.11.12B. Rain garden fills up the *Bottom* Zone in a smaller rain event

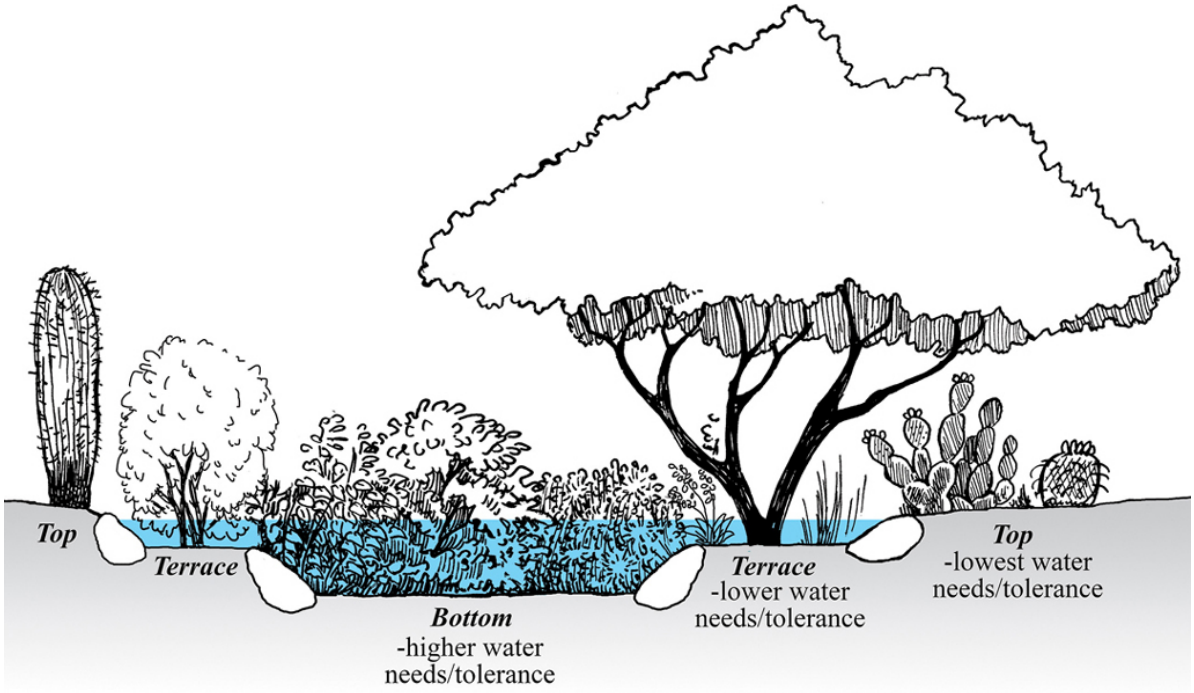


Fig. 11.12C. Rain garden fills up to the top of the *Terrace* Zone in a large storm event

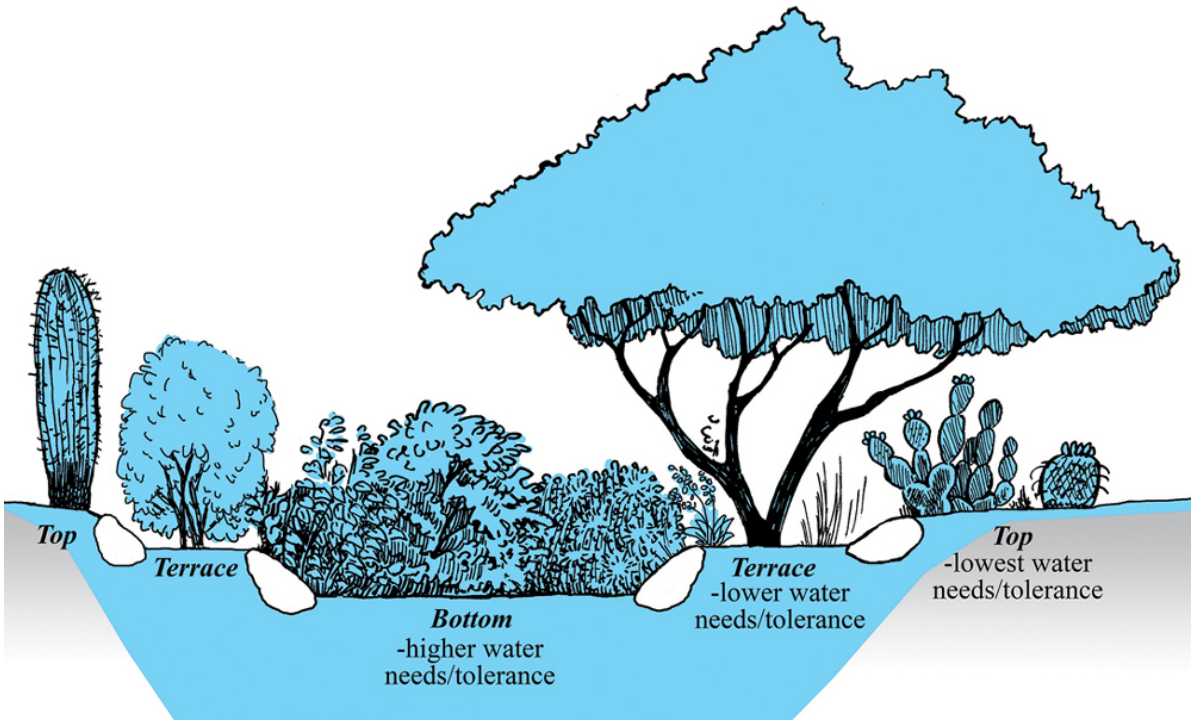


Fig. 11.12D. Once the passively harvested water infiltrates, it is held in the mulched soil, and pumped by the plants into their tissue

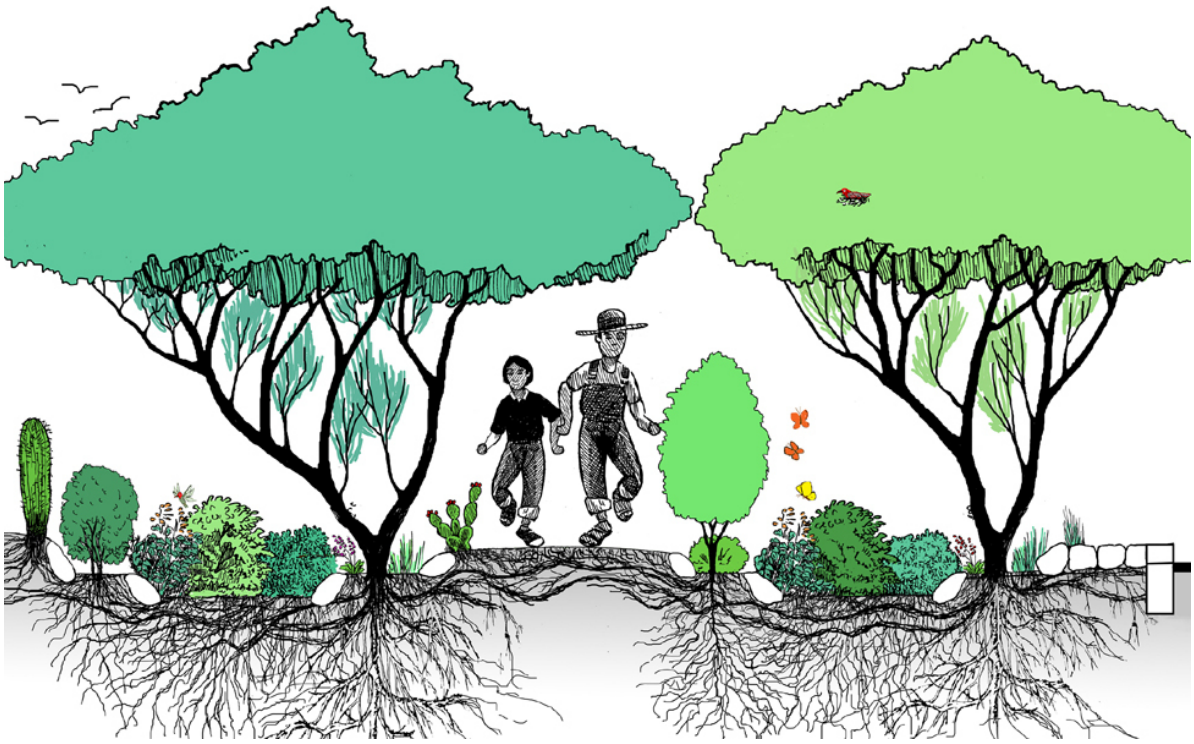


Fig. 11.12E. Think like vegetation. Tree and shrub roots often grow 2 to 3 times the diameter of the plant's leaf canopy (figs. 2.7A, B), so roots often extend to all rain garden zones and from one basin to another.

Bottom – typically bottom of a basin or diversion swale.

Prone to temporary pooling of water and cold air (cool night air pools in low spots). May partially fill with sediment.

Terrace – typically atop a terrace or pedestal within—or on bank of—a basin or diversion swale.

Shallower and less-frequent temporary pooling than in bottom zone.

Top – area beside—not *in*—a basin or on its banks, where plants' root crowns stay high and dry, but plants' roots can access water harvested in basin; top of berm.

Driest and warmest of the three zones (avoids cool-air pooling).

Note that the Rain-Garden Zone classification can also be used as a Greywater-Garden Zone classification when greywater is discharged into an earthwork.

Place more water-, sediment- and cold-tolerant vegetation in the *bottom* of infiltration basins and beside infiltration trenches or one-rock dams where soil moisture is relatively high. The more poorly soil drains, the more important it is to choose water- tolerant plants. Less water-needy plants and less water-tolerant plants should be placed on the well-drained *terraces*, pedestals, or slopes of basins and berms. Drought-tolerant plants, like cacti, and species with a low tolerance for standing water, like many fruit trees, are planted on the *top* or periphery of water-harvesting earthworks where roots can access harvested water, but the base of the plant stays high and dry.

Refer to plant books and knowledgeable folks at your local agricultural extension office for water needs, plant culture requirements, and climate requirements of exotic plants. To play it safe, put fruit trees on gradual pedestals or terraces within basins, or beside basins where roots can access harvested water while avoiding crown rot due to having too much water against their base (fig. 11.13).

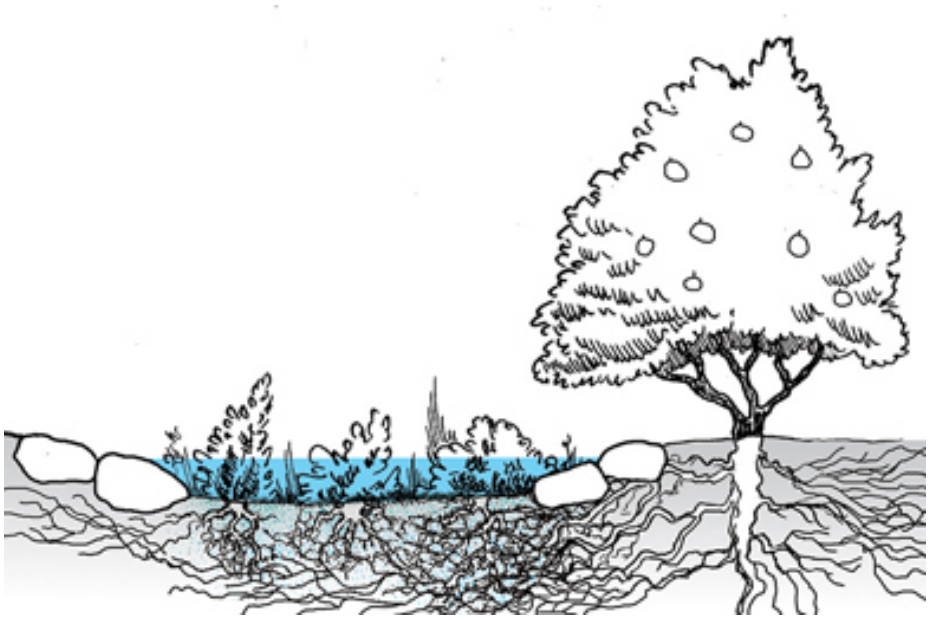


Fig. 11.13. A tree needing better drainage planted beside a basin (within the *Top* Rain Garden Zone) where its roots can easily tap the harvested water, while leaving the base of the tree (root crown) well drained and dry to reduce the chance of crown rot

Search "Rain-Garden Planting Zones" at HarvestingRainwater.com for more. There, you can also search "Multi-Use Plant Lists for Water-Harvesting Landscapes," which list ideal rain-garden zones and water requirements for plants in different bioregions. The plant appendix 4 of Volume 1 is another resource.

MAXIMIZING RESOURCES

Strive to turn your landscape into a producer rather than a consumer of resources by selecting plants that thrive within your rainwater budget while producing food, medicine, wildlife habitat, shade, soil-building nitrogen, beauty, a sense of place, craft materials, or fragrance (fig. 11.14).

Fig. 11.14. Food grown and processed at Tucson, Arizona, site that was watered entirely by harvested rainwater, and in some cases supplemented with household greywater

Look first to the native plant palette to meet your needs. Using natives gives you an immediate sense of place—a tangible connection to your site's ecosystem,

seasons, and traditional cultures who made use of native plants. The columnar saguaro cactus is a symbol of the Sonoran desert, and one of the many living calendars (living seasonal almanacs) and food plants that blanket the landscape. Saguaro blooms welcome spring's migrating white-winged doves, the lesser long-nosed bat, and the Mexican long-tongued bat. Its delectable fruit is the focus of the summer harvests and feasts of traditional Tohono O'odham and others, and the end of the saguaro harvest signals the arrival of the summer's monsoon storms. Native food plants are particularly rich in the Sonoran desert, with over 500 known edible plants representing approximately one-fifth of the desert's flora.[9] Not all bioregions enjoy such edible abundance, but all have their own native resource-producing plants providing food, medicine, dyes, wood, and fiber.

If you have a need that cannot be met by a native plant, consider planting an exotic species that can meet that need while thriving within your site's micro-climates and rainwater budget. Planting an ill-suited exotic will gobble up resources, and is unlikely to produce the fruit or grow to the size you desire if it does not get needed water and care. Do not plant exotic species that can become invasive pests. Deciduous salt cedars (*Tamarix ramosissima*) were brought into Arizona to control erosion on stream banks, but now aggressively dominate riparian areas all over the state. Huge resources are now spent to get rid of them.

Plant a diversity of species rather than just a few to see what works and what doesn't. You'll learn which plantings are worth replicating and which to avoid, and you can share this information with friends and neighbors. Even plants that die are resources in the form of knowledge and mulched organic matter.

Greater diversity extends your harvest and enjoyment. I love the wave of yellow flowers that covers blue palo verde (*Parkinsonia floridum*) and foothills palo verde (*Parkinsonia microphyllum*) trees in spring. The harvest of their barley-flavored seeds soon follows (pick green but full-sized, peel off the seed pod and eat the seeds or blanch and dry them for storage; you can soak the dried seeds in water to rehydrate and eat them later). These two related palo verdes set flowers and produce seed three weeks apart. Planting both varieties extends the show of flowers, the wildlife they attract, and the seed harvest. This principle applies to exotic vegetation too. For example, Valencia orange trees are harvested in my area from February through May. By adding an earlier-fruiting Marrs orange tree the harvest is extended from October to May.[10]

CREATING PLANT GUILDS

A *guild* is a harmonious assembly of living species and nonliving elements such as rocks or buildings that perform better through their cooperative interrelationships than they would as individuals. Many simple guilds are well known, like the corn-bean-squash combination used by Native American farmers. The nitrogen-needy corn creates a living trellis on which the nitrogen-fixing bean vine grows. The squash sprawls out over the soil benefiting from the nitrogen-enriched soil and the diffuse shade cast by tall corn plants. The broad-leafed squash casts a deep shadow on the soil that acts as mulch, retaining moisture in the soil, preventing erosion, and deterring weed growth. A nonliving element such as a building can enhance this guild by directing its roof runoff to the garden, and if placed to the west of the garden, by acting as an afternoon sunscreen, lowering ambient temperatures at the hottest time of the day and reducing water loss to evapotranspiration. The guild benefits the inhabitants of the buildings with food, beauty, and passive cooling, especially if the squash vine grows up a trellis on the side of the home.

Guilds occur naturally in all intact ecosystems, making it easy for you to observe, replicate, and experiment with them on your own site. An example from the Sonoran desert is the mesquite guild (box 11.4 , fig. 11.15).

Box 11.4. A Mesquite Guild

Fig. 11.15. A mesquite guild. Credit: April Baisan and David Harnish

The velvet mesquite tree (*Prosopis velutina*) is the central pillar of many Sonoran desert guilds. Flowers cover the tree in spring and summer attracting over 60 native pollinators.[11] Sweet and nutritious seedpods then form. Javelina, coyote, birds, and other wildlife consume the pods and leave manure behind. This improves the soil, as does decomposition of remaining seedpods, accumulation of fallen leaves, and the nitrogen-fixing action of beneficial bacteria living within root nodules on the leguminous tree.

This self-fertilizing island provides excellent wildlife habitat and a farmers' market of food plants. Beneath the mesquite, desert hackberry (*Celtis pallida*), greythorn (*Ziziphus obtusifolia*), and wolfberry (*Lycium* spp.) form an intertwining canopy of thorny foliage, with edible berries that birds love. A young saguaro (*Carnegiea gigantea*), and even a chiltepine (*Capsium annuum* var. *aviculare*), may grow underneath the mesquite, gaining protection from excessive sun and cold. The young saguaro will harden to the elements and eventually rise high above the mesquite, its flowers attracting insects, bats, and birds whose pollination

services will help produce heavenly fruits. The chiltepine is a wild chile with a devilishly hot taste. The birds feast on this fruit, along with that of the wolfberry, hackberry, and greythorn, and feed the soil with their phosphate-rich droppings. Digested seed from the fruit of the guild is dispersed as birds fly off and deposit manure in other areas. In fact, some seeds, such as the wild chile, need to pass through a bird's gut to enhance their germination. As naturalist and chile-addict Gary Paul Nabhan notes, chiltepines are so keenly associated with birds that many of the common names refer to this relationship: bird pepper, *pico pajaro*, *pajaro pequeno*, and so on.[12]

The plants and animals of this guild act as a living community, sustaining and improving itself through many beneficial relationships among its varied life forms. Wildlife is the mobile planter, expanding the community's territory. Vegetation works the soil, its roots breaking up and aerating the earth to allow more moisture infiltration when it rains. Plant leaves drop and collect, creating organic mulch, which stabilizes, protects, and ultimately becomes the soil. This mulch also creates conditions in which beneficial mycelium or fungi can thrive and expand the guild within the soil. The fungi sends out branching networks of root-like growth, further permeating and stabilizing the soil as it helps break down the mulch. Some of this mycelium also attaches itself to the roots of the plants, in effect increasing the plants' root network. The fungi then help provide the plants with essential nutrients and additional moisture, while the plants provide the fungi with sugars.[13]

Beneficial microclimates within the broad landscape enhance the guilds. Greater diversity of life forms and larger specimens can be sustained where more water collects, such as along drainages or within depressions; or where more water is conserved by shelter, such as within canyons or forests.

By encouraging or creating such beneficial guild relationships we can minimize long-term maintenance and costly inputs, and increase the potential of our landscape designs. Humans have regularly consumed fruits of the mesquite, greythorn, wolfberry, hackberry, and chiltepine, and many of the guild's plants are used as traditional herbal remedies. In certain markets, mesquite pods are ground into flour that sells for $14 per pound and the hot little chiltepines, once dried, command a price as high as $50 a pound. The saguaro fruit is too good to sell, you just eat it or turn it into wine.

Once you observe one guild, you'll see the basic pattern and start recognizing guilds throughout various landscapes. Master permaculture designer and teacher Tim Murphy originally introduced me to the mesquite guild through his teachings and "Hackberry/Walnut Guilds" article[14] on which much of this information is based. I went looking for the guild, found a version of it, and then saw guilds everywhere. I invite you to do the same.

So how do you re-create an existing guild or create a new one?

Mimic one. I'm always looking to see what plants naturally grow with other plants, especially in wild areas. If I find a group of healthy vibrant plants, I know that I've found a successful guild. I may not know why those plants are grouped together, I just know they are likely to grow well together if I plant this guild in similar soils and microclimates.

Becoming familiar with botany and plant families expands guild-creation skills. It can help you create an entirely new guild based on one you have observed in

nature. For example, if I have sufficient on-site water resources, I can create a new guild producing different resources (though likely requiring more water) by incorporating low-water-use natives and climate-appropriate exotics based on the mesquite guild. I could substitute the leguminous mesquite tree with a leguminous tree from the same botanical family (*Fagaceae*, Pea Family) such as a higher-water-use exotic carob tree (*Ceratonia siliqua*) or a low-water-use native desert ironwood tree (*Olneya tesota*). I could switch the native greythorn (*Ziziphus obtusifolia*) with a somewhat more water-needy sweet-fruited Chinese jujube (*Ziziphus jujuba*), spaced further to the perimeter of the guild due to its taller growth habit. The saguaro (*Cactaceae*—Cactus family) could be exchanged for another cactus such as the edible and thornless nopal (*Opuntia ficus-indica*) or a cholla, (*Opuntia* spp.) with its tasty flower buds. I could replace a small-fruited native wolfberry (*Lycium andersonii*), with a larger-fruited native variety (*Lycium fremontii*). The native chiltepine (*Solanaceae*, nightshade family) could be switched with a related nightshade such as a domesticated Anaheim chile (*Capsicum annuum*) or the beautifully flowering datura (*Datura wrightii*)—careful—it is poisonous if consumed.

New guild creations work most of the time. Replications of observed native plant guilds almost always work. Seek out guilds in your area. Learn about the plants that form them, then invite them to grow in your yard. Before you plant your guild, create the water-harvesting earthworks that will support it— plant the water before you plant the plants. For more on guilds see appendix 4.

SPACING YOUR PLANTS, AND PLANT SIZE

Locate and space all your plantings based on their size and water needs when *full grown*, not their size when planted. This will keep you from planting too densely, exceeding on-site water supply, or blocking a path with an overgrown shrub. A nursery plant that is 1 foot (30 cm) tall today could be a 10-foot (3-m)-tall and-wide shrub in the not too distant future. Landscaping books, knowledgeable plant nursery staff, and cooperative-extension master gardeners are great sources of mature-plant-size information.

Place large tree and shrub species in the middle of a planting area or along a fence or wall where they do not create a new barrier, but build off an existing one. Surround them with smaller-growing species placed around the edge of their water-harvesting basin so you can see and appreciate the beauty of all the plants.

TIMING YOUR PLANTING

Plant with the seasons. In southern Arizona, I plant nursery-grown perennials in late summer and early fall after summer rains bring moisture and when the heat of summer starts to subside. This way the plant has fall, winter, and spring to send roots into the soil and get ready for June's dry heat. With cold-intolerant plants like citrus I wait until just after the last spring frost to plant. This gets the citrus in the ground before the furnace heat of summer, but puts off exposure to the bite of cold until the plant is a little older and hardier. Ask local cooperative-extension master gardeners for recommended planting times in your area. Observe when plants flower, set seed, and germinate in your yard and in the wild. Plants whose seeds germinate with winter rains, such as four-wing saltbush and California poppies, should be seeded in late fall. Species that germinate with the summer rains, such as mesquite and devil's claws, are seeded just before or after the first summer rain.

The time when you plant is not as important if you irrigate, but planting with the seasons can reduce the need to irrigate and increase plant survival. If you need to move a plant, see box 11.5.

Box 11.5. Moving Plants After They've Been Planted

If in the first year after planting you realize you made a mistake in the placement of a tree or shrub, you can dig it up and replant it elsewhere. Try to keep the soil around the rootball intact and, if possible, move the plant when it is dormant (usually in the winter season). Move the plant when the soil is not saturated with water nor too dry.

TOOLS AND MATERIALS FOR PLANTING

Tools: to plant trees and shrubs: a pointed shovel or hoedad, pick, and wheelbarrow. A mechanical ditch digger, trackhoe, or backhoe is helpful for digging multiple large holes.

To plant grass or wildflower seeds you need a hard bow rake or field rake (leaf rakes are too flimsy) to loosen the soil's surface; seed is then sown and a thin layer of soil raked over them.

To irrigate new plantings, a garden hose, soaker hose, drip-irrigation bucket (a 5-gallon or 20-liter bucket with a 1/8th-inch or 3-mm hole drilled in the bucket's side just above its base to slowly drip water), or conventional drip-irrigation lines are typically used to get the plants established before supplemental irrigation is ceased.

Materials: nursery-grown plants, seed, organic mulch, and optional fencing.

PLANTING

When you are ready to plant, set plants in their pots (or without pots if bare-root plants are used) on the ground where you will later be planting them. Again, imagine how big they will be when mature (figs. 11.6A, B). Readjust their locations if needed, then plant.

When you put in a 5- to 15-gallon (20- to 57-liter) plant (box 11.7), use the following steps (see fig. 11.16):

- Dig a hole up to twice as wide (though I typically dig only as wide) as, and as d as (but no deeper than) the root ball contained in the planting pot (see box 11.(Water-tolerant plants can be placed within water-harvesting basins. If the plant not tolerant to temporary soil saturation, place it beside the basin (fig. 11.13); c place it on a gradually sloping pedestal within a basin.

Box 11.6. Planting Study Saves Our Backs and Wallets

Two experiments in Tucson, Arizona tested the long-held belief that trees planted in desert soils need to be planted in back-breakingly deep holes backfilled with costly imported soil and amendments. Argentine mesquite trees (*Prosopis alba*) transplanted from 24-inch (60-cm) box containers, and oaks (*Quercus virginiana*) transplanted from 5-gallon (20-liter) containers, were planted under a variety of conditions. Some were planted in holes 5 feet (1.5 m) deep and wide, while others had holes no deeper than the root ball of the trees. Some holes were backfilled with amended soil, some just with native soil, and some with native soil capped with a surface mulch of composted yard waste.

The findings are cause for celebration! The study concludes by saying, "Organic amendments *in* the backfill do not improve and may reduce shoot and root growth. A shallow, wide hole with unamended backfill and a surface mulch is an acceptable, if not superior, planting standard for trees and shrubs."[15]

Interestingly, researchers found that trees planted in deep holes tended to settle and sink into the uncompacted soil beneath them. In addition, caliche (a hardpan composed of calcium carbonate) was not the impenetrable barrier it was typically thought to be, since roots from the trees frequently penetrated it, even if the shovel did not.

For more see "Effect of Planting Practices on Tree Performance" by Jimmy L. Tipton, Elizabeth Davison, and Juan Barba in Series P-107, Cooperative Extension Station, The University of Arizona, Tucson, U.S. Department of Agriculture.

Box 11.7. Size Matters When It Comes to Water Needs

According to George Montgomery, Curator of Botany at the Arizona-Sonora Desert Museum in Tucson, a nursery-grown, low-water-use native tree planted from a 5-gallon (20-liter) nursery pot needs about two years of supplemental watering before it can survive on

rainfall alone. However, trees planted from 24- to 36-inch (60- to 90-cm) containers can take up to ten years of supplemental watering to become established.[16]

Large containerized plants are utilized to get a big plant *now*, but interestingly, smaller nursery stock planted in the ground can grow faster than bigger stock. I have found that 5-gallon trees planted at the same time as 15-gallon (56-liter) trees outgrow the 15-gallon trees in 3 to 5 years.

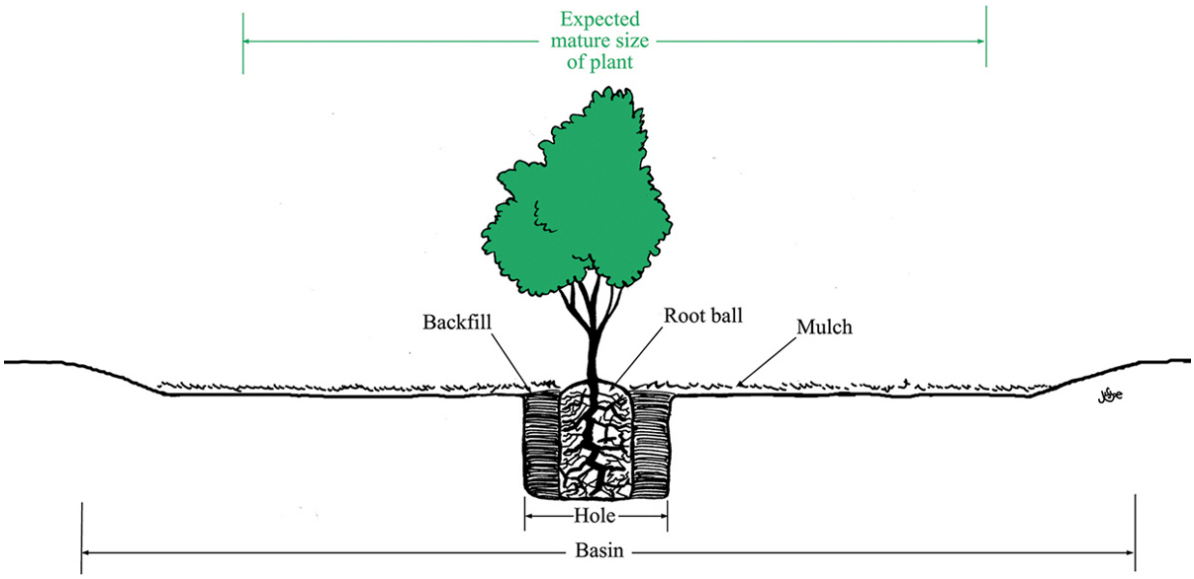


Fig. 11.16. A tree planted within a basin without hard-pan. Ideally the basin (or the cumulative area of a number of adjoining basins) should be 1.5 to 3 times the expected canopy diameter of the plant at maturity (if space allows), since most water used by plant is from the root zone outside the canopy drip line (see fig. 2.7B). However, even one small basin is better than no basin.

- Check for correct hole depth by placing the plant— still in its pot—into the ho The top of the dirt within the pot should be level with, or slightly above, the to the surrounding grade. Do not place the root crown (the point where the base/trunk of the plant enters the soil and root growth begins) at the lowest poi within a basin because the root crown of some species could rot if water sits in t basin too long. Take the pot back out of the hole and make any needed adjustments to hole depth.

- Loosen the plant root ball from the sides of the pot by carefully laying the potte plant on its side and pressing the side of the pot as you gently roll the potted pl 360°. Do not press so hard that you break up the root ball, which breaks more roots and root hairs and reduces the plant's chance of success. Tap the bottom o the pot to loosen the base of the root ball. Pick up the pot, place a hand on top

the root ball, and tilt the pot so the root ball slides into your waiting hand(s). A friend can lift and tilt while you catch. If some of the dirt falls off the root ball during this operation, you may need to put some backfill in the bottom of the l before placing the plant in to maintain the right elevation in the hole.

- Check to see if the root ball is rootbound or pot-bound, a condition where the roots are tightly wound in circles within the pot, resulting in stunted growth. If plant is potbound, take it back to the nursery and exchange it for one that is no

- Having removed the plant from the pot, *carefully* place (do not drop) it in the h centering it and setting it upright. Tilt the root ball in the hole if necessary to m the trunk stand up straight (fig. 11.17). Backfill with the same soil you dug out the hole. Typically you should not amend this soil, though if the majority of th soil you dig out is caliche hardpan, you may want to replace some of the caliche with a better-draining soil. Lightly compact the backfill with your hands, feet, c the best way— by soaking the backfill with water, which will give the plant a thorough watering at the same time.

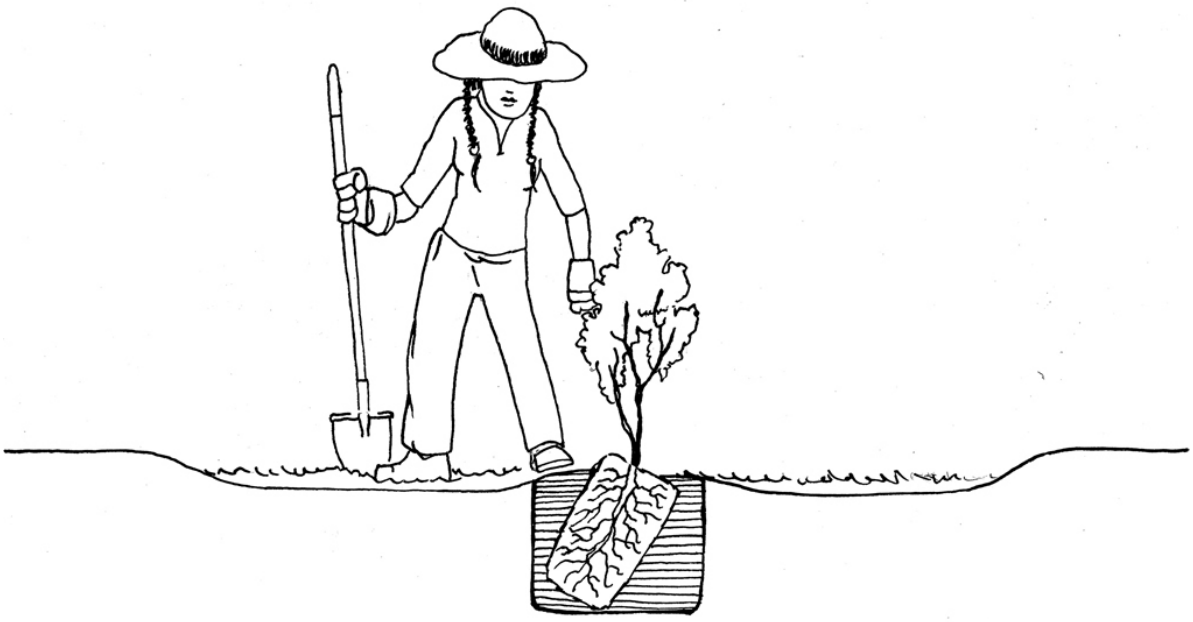


Fig. 11.17. Tree growing from its root ball at an angle is planted with the root ball at an angle so the tree is set vertically in the ground. Planter is compacting the soil around the root ball with the heel of her boot.

- Do not prune newly planted trees or shrubs as this will deter root growth; howe some grasses will transplant more successfully if they are trimmed 25% once planted.

- If you are putting out seed for wildflowers or native grass in the water-harvestin basin, spread the seed out and rake it into the top 1/4 inch (6 mm) of the basin soil.

- Mulch the soil's surface starting about 4 inches (10 cm) away from the trunk of plant—do not place mulch next to the plant's base—and extend it at least 2 fee (0.6 m) beyond the drip edge of the plant's canopy. Better yet, mulch beyond tl drip line to the entire basin (see chapter 7 for more). Seeded areas should have a very light mulch, otherwise germination will be inhibited.

- Give your plants a thorough watering.

- Reuse plant containers or recycle them at a plant nursery that grows out plants.

For less water-tolerant plants or within basins with hardpan and poorer drainage, create a well-drained pedestal or terrace within, or on the edge of, the basins. Plant in a hole dug shallow enough so the top third of the root ball is above the bottom of the basin, then backfill with dirt compacted with foot and shovel to create a slight, gradually sloped pedestal around the plant. Do not place the top of the pedestal higher than the upper edge of the basin. The pedestal will keep any temporarily standing water away from the base of the plant, so it drains better, and reduces chance of disease (figs. 11.18A, B).

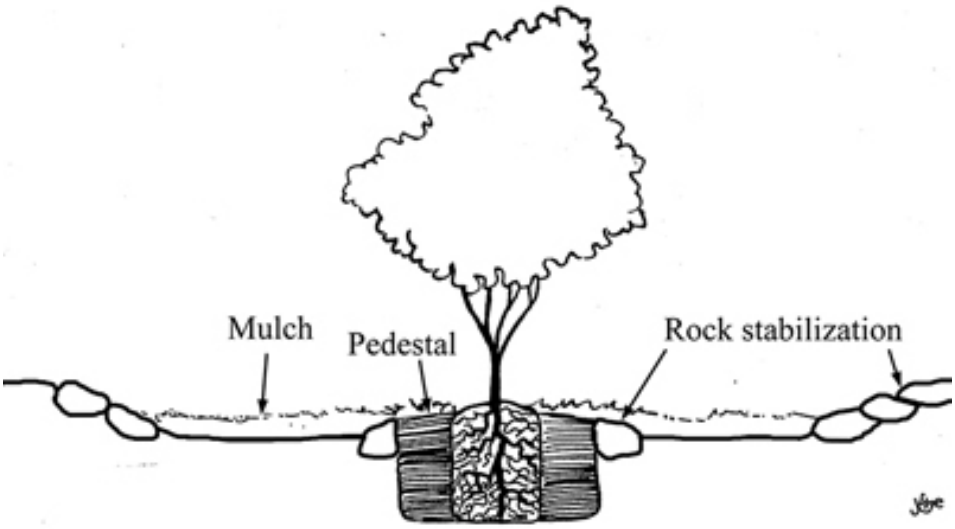


Fig. 11.18A. Planting and pedestaling within a basin for better drainage around the base of the tree (its root crown). Note: Stabilizing the slope of pedestals and terraces will greatly reduce their erosion.

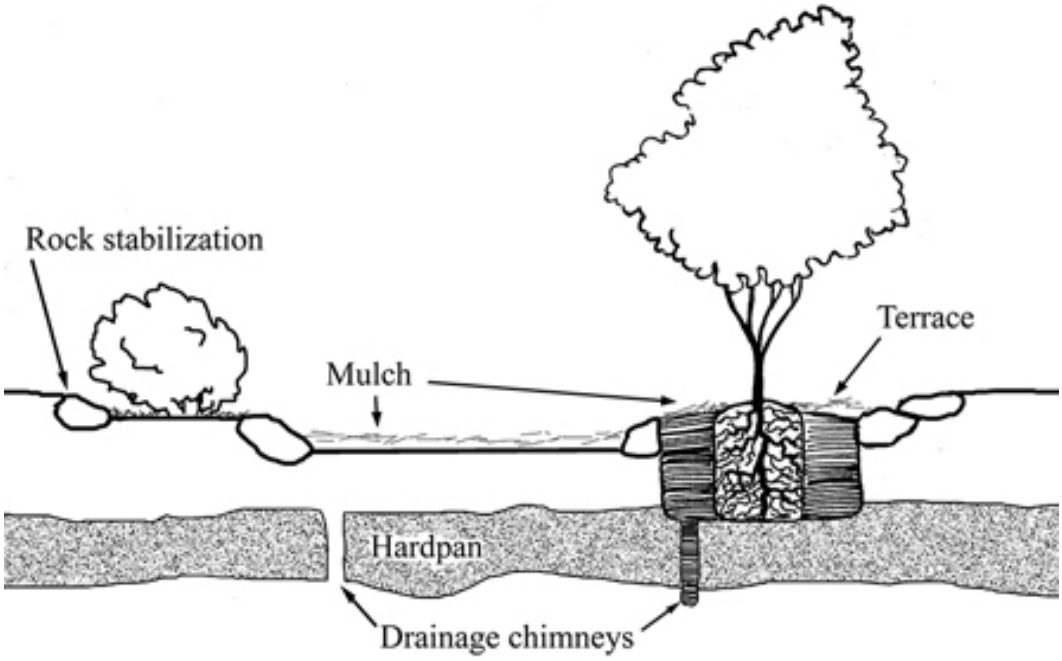


Fig. 11.18B. Planting on a basin-side terrace for better drainage around the base of a tree. Due to the presence of poorly draining hardpan, chimney holes have also been dug through hardpan beside, but not beneath, root ball to avoid root rot due to excessive water. Fill these chimney holes with soil.

Broadcasting seed in water-harvesting earthworks, rather than planting nursery stock, is often a less expensive way to revegetate a broad area. Perennial plants

grown in place from seed have deeper and wider root growth, and are more drought tolerant and vigorous, than similar plants transplanted from potted stock since they were never hemmed in by a pot.

FENCING

If animals might eat or trample tender young plants or seeded areas, fence each plant individually or place them in a protected yard. A two-foot-high wrapping of chicken wire held in place with two stakes keeps rabbits, chipmunks, chickens, and pack rats at bay (fig. 11.19). (The inconvenience of the fencing usually deflects them to hardier, established, unfenced vegetation.) Protection against javelina or destructive dogs requires 3-foot (0.9-m) tall hardware cloth or field fencing staked with two to four posts. Keep out deer and goats with 6- to 8-foot (1.8- to 2.4-m)-tall, well-staked field fencing. Keep goats, horses, and mules entirely away from the main branches and trunks of plants they could kill by eating them to the ground or stripping all bark. Trees with *well-protected, out-of-reach bases* can eventually grow a shade canopy over animals with just the lower branches being pruned/chewed (fig.11.20).

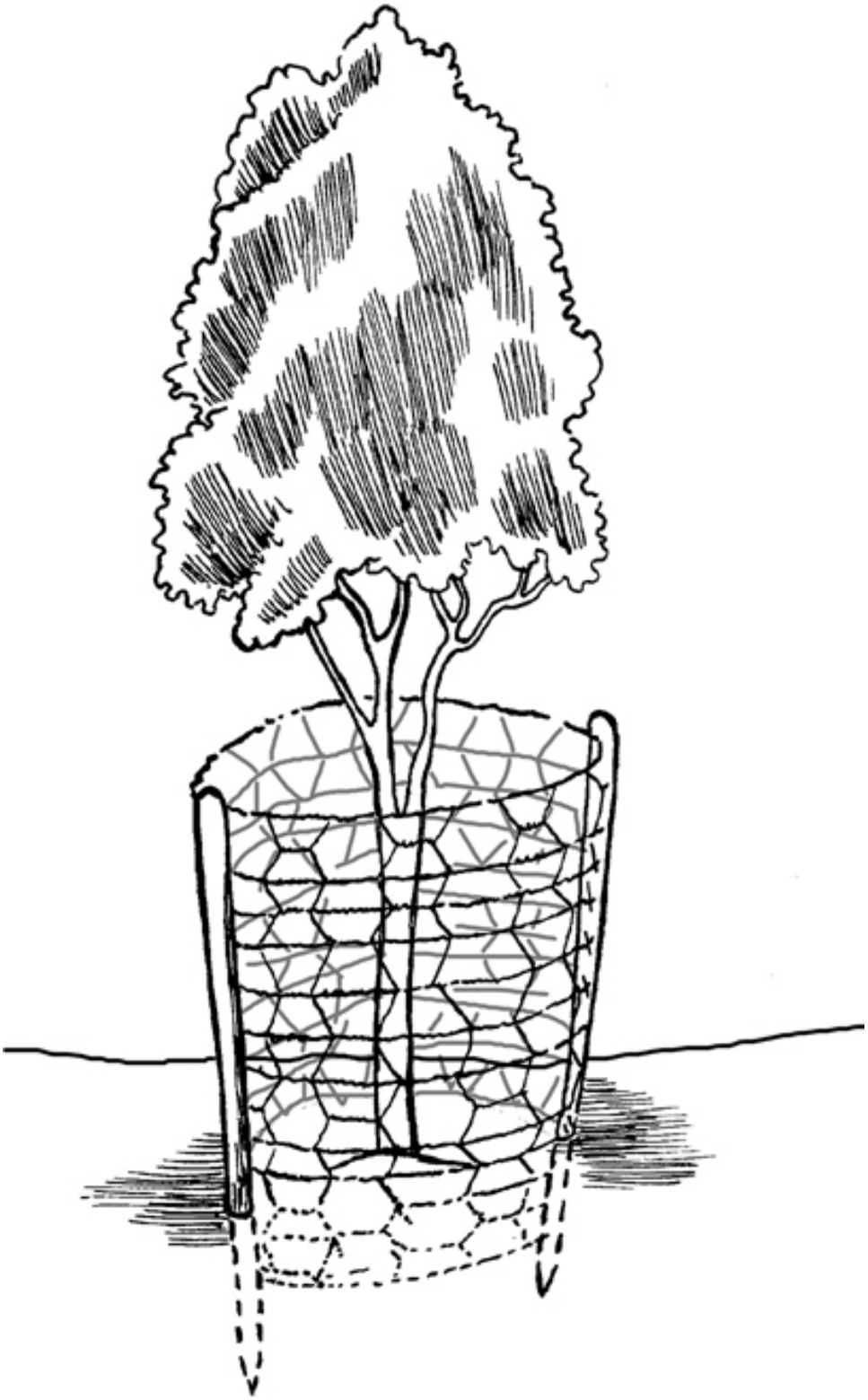


Fig. 11.19. Protection from browsing small animals. Can bury lower part of fencing if necessary.

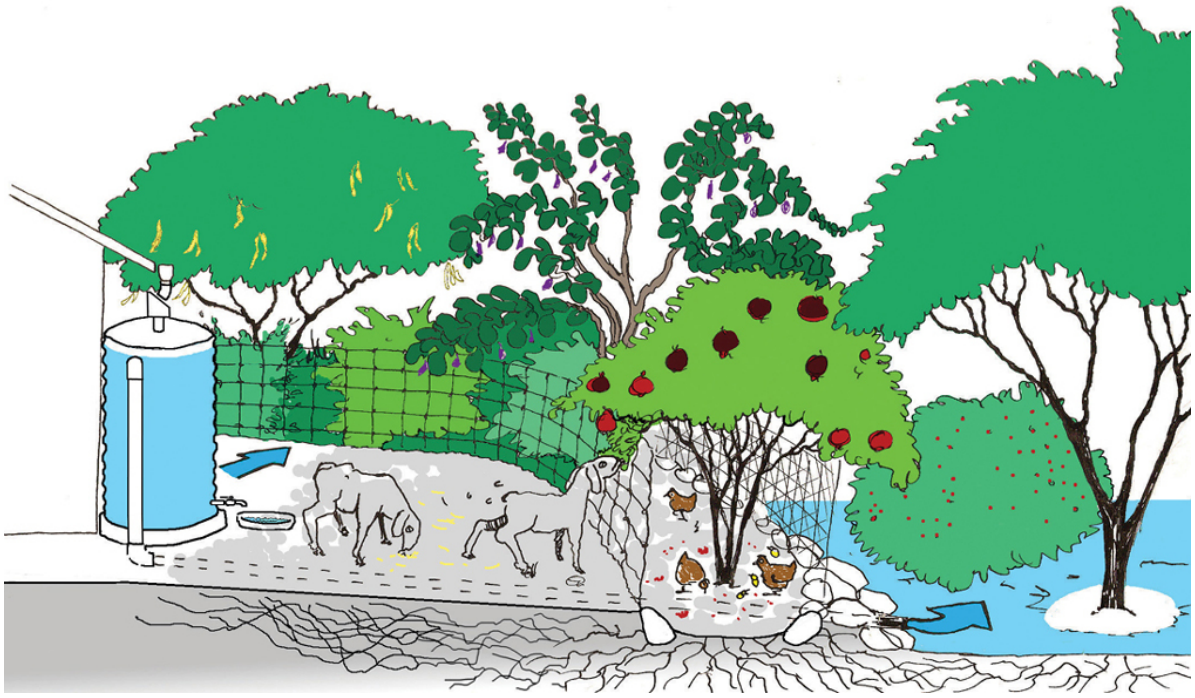


Fig. 11.20. Fencing protects the base of vegetation from browsing animals, so the plants can provide a protective canopy of shade, while the lower portions are sustainably browsed and pruned by the animals. Adapted from *Living Together: A Permaculture Site Assessment for the Phoenix Zoo Children's Trail Farm* by the Phoenix Permaculture Team, 1997

STAKING

Do not stake trees unless they cannot support themselves. If you must stake a tree, stake it loosely so it can bend and sway in the wind, moving like an exercising muscle, developing strength and flexibility (fig. 11.21). Remove stakes as soon as the tree can support itself. An alternative to staking is carefully thinning a tree's canopy to reduce its size until it can support its own weight and mass. I avoid having to stake by purchasing nursery trees that are not staked in the first place.

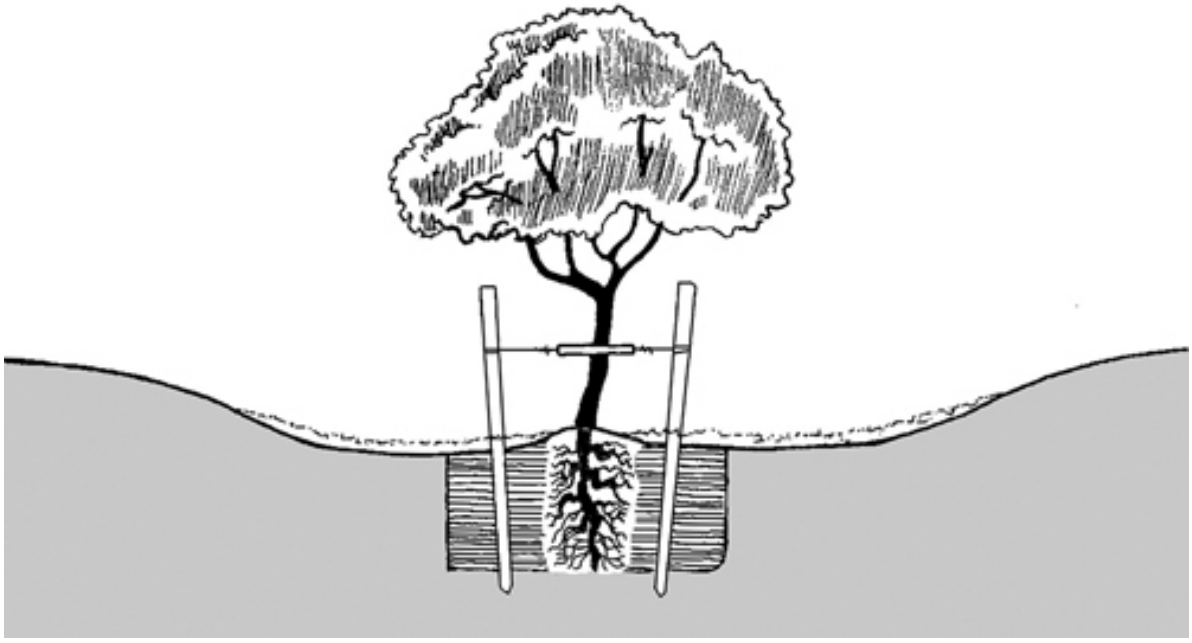


Fig. 11.21. Loosely staked young tree. Stake trees only if necessary, because the more plants can bend and sway with the wind, the stronger and more flexible they will become.

MAINTENANCE

Check your plants regularly, making sure they get the watering, fencing, pruning, and weeding they need.

WATERING

Watering schedules will vary depending on climate and plant species. Local landscaping books, and cooperative extension and nursery staff can advise how much and how often to irrigate plants, though you'll find your water-harvesting earthworks can reduce or eliminate the need for irrigation once the plants are established. In my climate, I water newly planted low-water-use *native* vegetation (transplanted from 1- to 5-gallon or 4-to 19-liter-sized pots) for the first two to three years to get them established. Larger plants and some exotic plants will need longer supplemental watering. I water heaviest the first year, giving most low-water-use trees and shrubs a good soaking every other day for the first three weeks (in warm/hot growing season), making sure the entire root ball is watered. Then I back off to one good soaking per week until winter, when I cut back to watering once every two weeks. When the weather warms up, I boost the frequency back to once a week.

By the second year I begin to gently wean plants off supplemental irrigation, reducing waterings to once a month. By year three, I limit monthly watering to summer, though I'll give one or two extra waterings in a drought. From that point on, if I've selected and planted vegetation well and rains are reliable, plants grow well on rain and supplemental greywater alone. But, if I want certain plants to grow more quickly, I continue supplemental watering until they've reached the desired size, then gradually wean them off. Directly observing plants, and adjusting watering to their condition, is always superior to unchecked automatic waterings. During summer, irrigate at night or early morning when temperatures and evaporation rates are lower.

Observe plants in your yard and in the wild to learn about their health and habits through different seasons. Native, low-water-use, dryland plants have many adaptations that sustain them through dry seasons and droughts. Some drop their leaves and go dormant, then burst with green leaves and colorful blooms when rains arrive. During drought dormancy, the stems remain flexible when bent, as long as they are healthy. Expect and appreciate these seasonal changes. But in drought years, if your established plants show signs of drought stress as opposed to drought dormancy, give them a boost with supplemental water to carry them through until it rains. Do not water so much that they respond with the abundant growth characteristic of wet seasons. Signs of drought stress can include abnormal leaf drop, curling or yellowing of leaves, and shriveling of cacti. Keep taking hikes and carefully observing native plants to detect the differences between healthy adaptation to drought and excessive suffering from drought stress.

Native and non-native plants that are not well established cannot tolerate water stress, so water them accordingly. Poorly adapted non-native plants or high-water-use natives may be dependent on supplemental irrigation throughout their lives. If you are using an automatic drip irrigation system, consider resetting it to come on only when you turn it on when plants actually need it, saving water and money. At the very least, change automatic timer settings to correspond with the seasons—cut back in cool and wet seasons and install a rain sensor that shuts off the system when it rains. If most plants are doing fine, do not turn on drip irrigation systems to water just one or two plants in the landscape; water those few plants with a hose instead. See box I.2 for statistics on the efficiencies of automatic drip versus manual hose irrigation.

Use a plastic 5-gallon (20-liter) bucket with a 1/8-inch (3 mm)-diameter hole drilled in its side for an efficient, inexpensive, and mobile manual drip-irrigation

system. Fill the bucket with water, carry it to where it is needed, and the water will empty through the hole in about an hour. Place the bucket farther from the base of plants as their roots grow, and use it only when the plants need supplemental water, typically when they are becoming established and perhaps during drought (figs. 11.22A, B). Don't buy a new bucket. Get a used one, and turn a waste into a resource. Donut shops sell used buckets cheap.

Fig. 11.22A. Bucket drip irrigation. More expansive root growth of trees is encouraged by placing drip-irrigation buckets beyond the drip edge of trees' canopies, as buckets also irrigate newly planted understory plants. Note: The curb cut directs street runoff to the tree's basin (see chapter 8 for more). Use buckets with metal handles. Plastic handles break.

Fig. 11.22B. 1/8-inch (3-mm)-diameter hole in the side of the bucket, just above bucket's bottom, discharges the water like a drip-irrigation emitter. Place bucket beside newly planted vegetation when watering. Note on bucket reduces theft of bucket when watering the public right-of-way.

Encourage vegetation to extend roots deep and wide so plants will be less likely to blow over in strong winds and have increased access to residual soil moisture in dry seasons and droughts (fig. 11.23A, B). Applying water only near the base of the plant will result in a stunted ball of roots. Instead, spread water out so roots will follow. Multiple earthworks surrounding plants will lure roots in many directions. Once plants on drip systems are established, move the emitters about 6 inches (15 cm) farther from the base of the plant each month during the growing season to encourage more extensive root growth. Many dryland plants draw most of the water they use from the root zone *outside* the plant's canopy drip line (fig.

2.7B).[17] Mimic the philosophy of Zimbabwean water farmer, Zephaniah Phiri, who says to his plants as he puts them in the ground, "There is the water; now go and get it!"

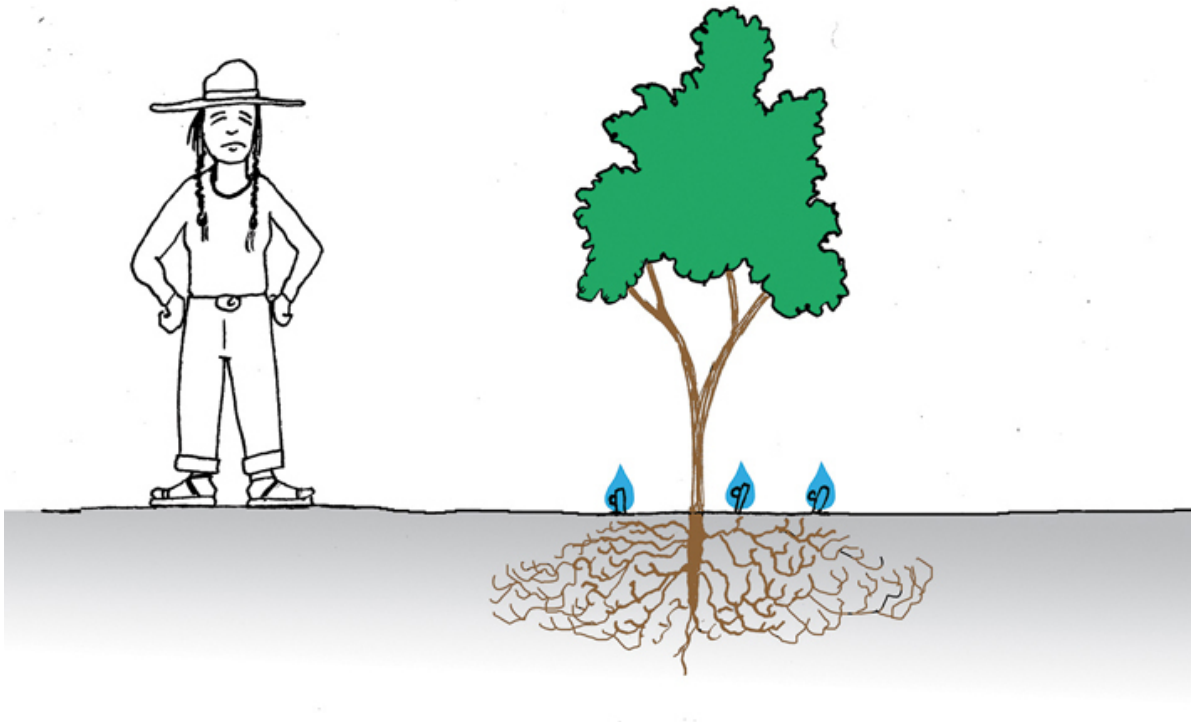


Fig. 11.23A. Drip-irrigation emitters installed and left at the base of a tree grow a stunted, concentrated pivot ball of roots. Such root growth makes the plant more susceptible to drought stress and to being blown over in strong winds.

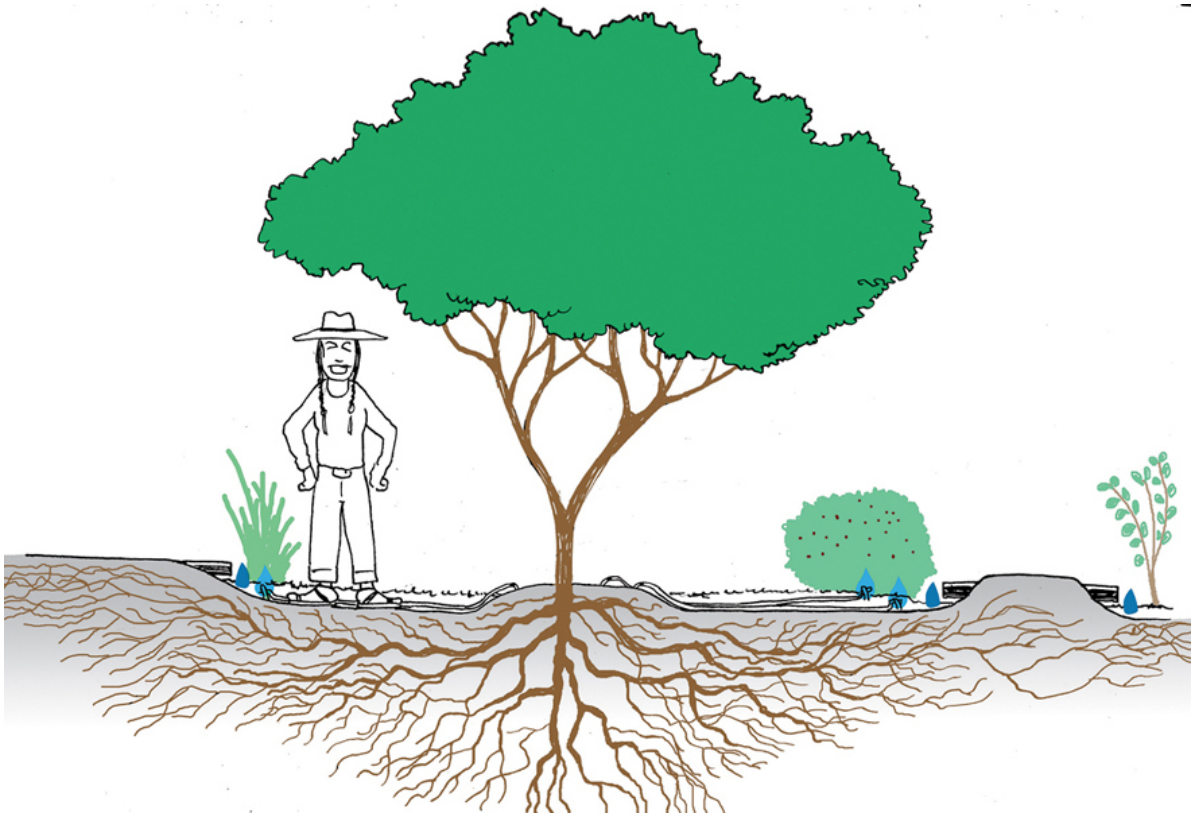


Fig. 11.23B. Expansive, stable, and drought-resistant growth of roots can be stimulated by using wide basins, multiple basins, or drip-irrigation emitters initially installed at the tree base, then periodically moved farther out to encourage root growth. Note: If greywater is distributed to the tree, branching or splitting its flow so greywater discharges on both sides of the tree helps encourage extended root growth.

PRUNING

Ordinarily plants do not need to be pruned, and are very healthy when they aren't.

But the need to prune can arise in urban areas with heavy human activity such as along pedestrian paths, within parking lots, or around buildings. In these areas, pruning can maintain pedestrian and vehicle access, open up a space, help transform shrub trees into canopy trees, and regain winter solar access otherwise shaded out by low-growing branches (see drawing of tree pruned for optimal winter sun and summer shade in chapter 4, Volume 1).

But such pruning should not occur until a plant is well established, three years or more after planting. This is because auxins (hormones made in the tips of branches) travel to the roots to assist in root establishment. The more root growth there is, the more drought-tolerant a plant will be, and the better it will be

anchored against strong winds. Pruning removes the sources of auxin, thus root establishment is slowed. The only pruning I recommend early in a tree's life is to prune off broken branches at their point of origin.

If you prune plants after their establishment, minimize cuts and nurture the natural growth form of the plant. Many dryland trees and shrubs are naturally multitrunked, with a draping, well-balanced canopy that provides cover for wildlife, shades the bark of the plant, and keeps the ground surface cool. Do not prune such plants into a single trunk or they will become top-heavy, requiring staking and continuous maintenance (figs. 11.24A, B).

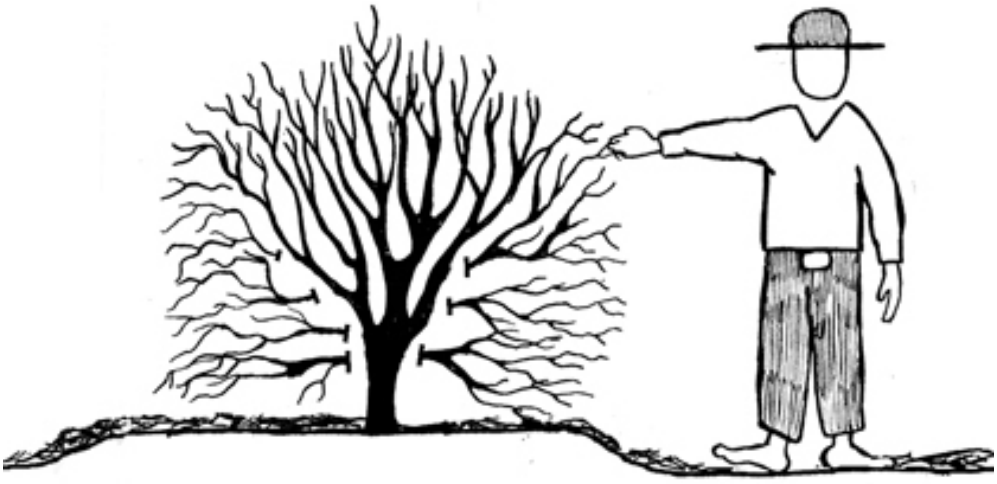


Fig. 11.24A. Pruning a young dryland tree to encourage upward growth, while retaining natural, multitrunked shape. Note: Such pruning is necessary only if you are trying to create a shade canopy you can get under. Never prune more than 25% of the plant. And never "top" or prune the upward growing branches.

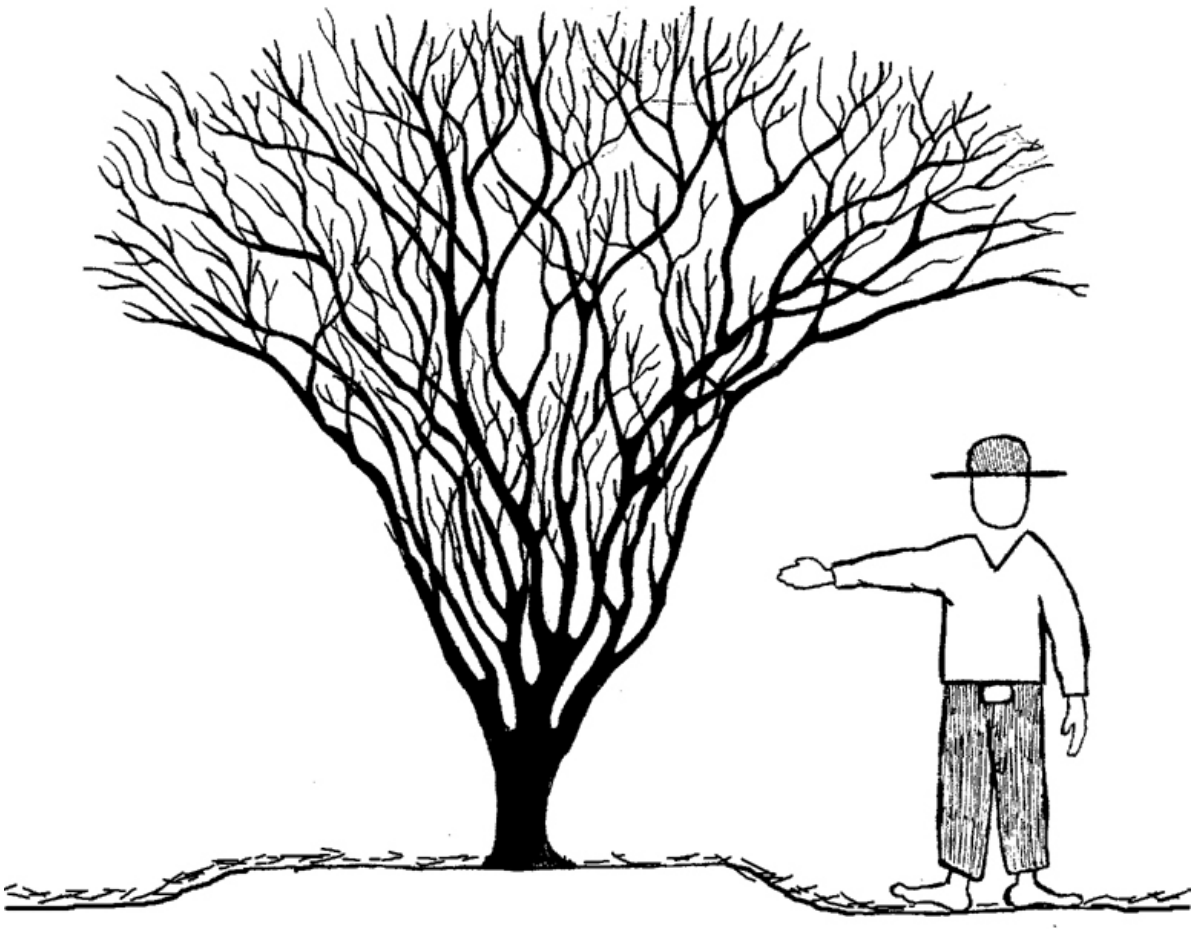


Fig. 11.24B. Tree after pruning and growth. Note recycling of cut-up prunings as mulch.

A good pruning cut consists of a direct line from the outside edge of the branch bark ridge (a raised furrow of bark on top of a branch) to the outside edge of the branch collar (a raised furrow of bark on the underside of a branch). The meristematic tissue in these raised furrows will grow over the edges of the cut to heal the cut. Make clean—not jagged—cuts so they heal quickly. Sharp saws or pruning shears are far better than hatchets for making clean cuts. Scissor-action *by-pass* hand-pruning shears (see fig. 7.6B) can be used to cut branches under 3/4 inch (2 cm) in diameter. Avoid using *anvil-type* pruning shears or loppers that work by directing a cutting blade against a flat surface, crushing plant tissue as it cuts. For larger cuts, use a sharp pruning saw and the three-step saw method shown in fig. 11.25 to prevent the weight of large branches from splitting or tearing the plant at the cut location.

Do not leave the dreaded "bad-pruning stubs" on plants (see final cut on fig. 11.25). These pose hazards to people and they create entry points for insects and disease. Leave the cut surfaces dry—do not apply tree wound treatments, paints, or pruning compounds. Such compounds may seal in harmful bacteria and interfere with the plant's ability to naturally seal wounds.[18]

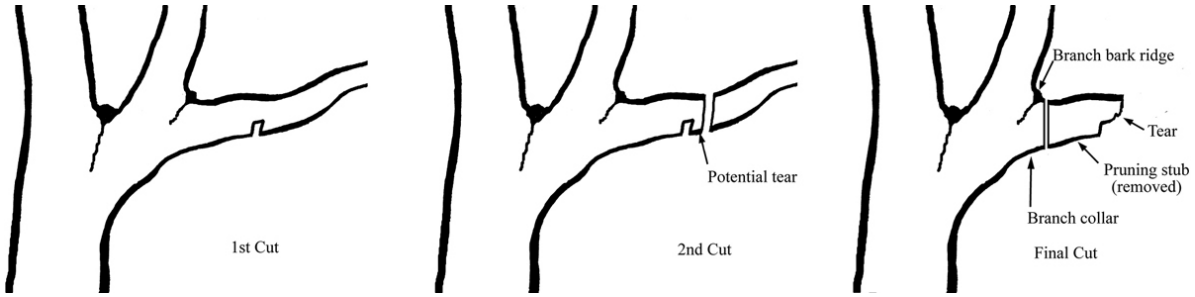


Fig. 11.25. A three-step technique for pruning a large limb: First, cut from the underside of limb, upwards one quarter to one third of the way through the branch. Second, cut from the top of the limb downwards, sawing the branch completely off. Third, cut from top to bottom to remove the stub. Cut from the outside edge of the branch bark ridge to the outside edge of the branch collar, so the meristematic tissue can heal the cut.

Cut or shred pruned plant materials into 4-inch (10-cm) or shorter pieces, and use these resources onsite by laying them on the ground as a water-conserving mulch around the plants they came from (fig. 7.6B). As the prunings decompose, their nutrients are recycled back into the soil and eventually back into the plant (fig. 7.6C). Large branches can be used for building projects or firewood.

WEEDING

What is a weed? A plant whose virtues have not yet been discovered.

—Ralph Waldo Emerson

You can dig out or pull *unwanted* weeds, especially if they are invasive non-native species. Pull them before they flower and seed, and drop them in place to beneficially decompose into the soil.

"Weeds" that are desired are no longer weeds at all. For example, I once pulled invasive Bermuda grass (*Cynodon dactylon*) until I noticed my chickens loved to eat it. Now I let it grow, but only where my chickens can pull it for me. Purslane (*Portulaca oleracea*) is a succulent, low-growing "weed" that I find delicious and

nutritious. I used to kill purslane, now I encourage it and even plant "improved" larger-leaved varieties, and eat them both.

For more information on the virtues of certain weeds see appendix 4.

GOING ORGANIC: NATURALLY ENHANCING THE HEALTH OF THE SOIL, THE PLANTS, AND THE SYSTEM AS A WHOLE

In *The Soil and Health: A Study of Organic Agriculture*, Sir Albert Howard describes how the health of plants and those who eat the plants—people and animals—ultimately depend on the health of the soil plants grow in. The system's health also depends on the quality of water that travels over and through the soil, and then is taken up into plants, animals, and people. We are what we eat and drink. Some of us eat animals, and all of us—including animals—eat plants, so we should be concerned about what the plants "eat and drink." Studies show that organic foods are healthier and higher in nutrients than nonorganically grown foods.[19] I recommend practicing organic methods of gardening, farming, and landscaping in which no non-natural pesticides, herbicides, or fertilizers are used. Organic methods improve our foodsheds, watersheds, and airsheds, which are all interconnected. See appendix 4 for resources on growing and eating organic foods.

THINNING: OBSERVE YOUR PLANTS AND SPACING

Thinning is needed when plants' water demands begin to exceed your landscape's water supply. This can happen as landscapes grow and mature and as volunteer plants increase. In wet years, densely spaced plants look great since there is plenty of water to go around. But when drought hits, you will see signs of stress such as drooping plants, leaf drop, or even die-back of parts or all of some plants. Thinning reduces competition for water. It also reduces the threat of fire since higher soil moisture will keep remaining plants green, and dead fuel wood will be removed and turned into mulch.

When thinning, begin in densely crowded areas and take out short-lived, fast-growing pioneer plants before you take out long-lived, slow-growing, higher order plants. In Tucson I remove fast-growing, weak-wooded four-wing salt bush (*Atriplex canescens*) before removing slower-growing, medicinal Mormon tea (*Ephedra trifurca*), or the dense-wooded, fruit-producing desert hackberry (*Celtis spinosa*). When deciding what to thin, try to preserve higher value plants such as food producers. Cut up or chip the thinned plants, and use them to mulch land

surfaces to recycle nutrients back into the soil, increase rainwater infiltration, and reduce loss of soil moisture to evaporation.

You may need to remove or transplant high-wateruse plants that have been misplaced in areas with insufficient water supply. This becomes more apparent as plants grow and water needs increase. I planted an orange tree on the periphery of my property before I understood the concept of oasis zones. This plant received plenty of harvested runoff in wet seasons but not enough in dry seasons, so it was stunted and never bore fruit. Once transplanted into the wetter oasis zone beside my home, the orange tree received more rooftop runoff in the wet season and household grey-water year round. Now it grows well and bears fruit.

Consider thinning vegetation if your site needs more direct sunlight. An ornamental palm tree on the south side of our home prevented winter sun from reaching our south-facing windows, leaving the home frigid. We removed the ill-placed tree, and now the winter sun coming through the windows passively heats our home. See chapter 4, Volume 1 for more information on designing with the sun.

MULTIPLE FUNCTIONS OF VEGETATION

VEGETATION AS LOCAL SOURCE OF FOOD AND FOOD SECURITY

Astonishingly, in the United States, food typically travels from 1,500 to 2,500 miles (2,400 to 4,000 km) from a farm to your table.[20] Yet, plants in your landscape can produce food right outside your door (figs. 11.26 and 11.28). One hundred fruit trees scattered throughout a thousand-home neighborhood are just as productive as a hundred trees planted in a 1-acre (0.4-ha) irrigated orchard. A thousand such neighborhoods could produce as much as a thousand acres (404 ha) of orchard.[21] Besides food, orchards integrated with homes and neighborhoods provide passive cooling, living playgrounds, windbreaks, erosion control, beauty, and stronger local economies. Watering these trees and other food-producing plants with harvested rainwater and on-site greywater drastically reduces the strain a groundwater-irrigated orchard puts on community water resources. In addition, it simultaneously eliminates the fossil fuel consumption needed to harvest, package, transport, and sell the distant orchard's produce to you.

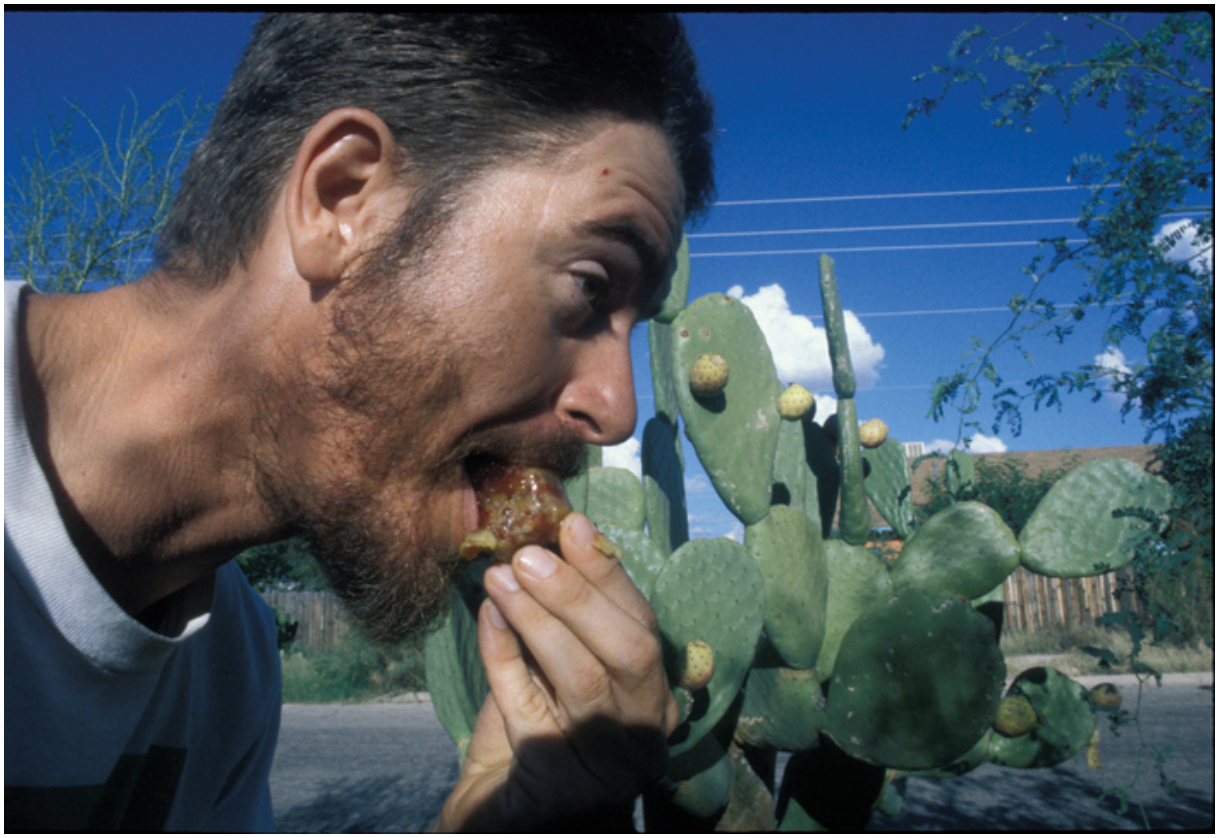


Fig. 11.26. Rodd Lancaster enjoying rain-irrigated, neighborhood-grown cactus fruit. In addition, the cactus pads can be cooked as a vegetable.

VEGETATION AS OUR PLANET'S LUNGS

According to the *Citizen Forester's Guide: The Simple Act of Planting a Tree*, a big tree can provide a day's worth of oxygen for up to four people.[22] According to the U.S. Department of Agriculture, "One acre of forest absorbs six tons of carbon dioxide and puts out four tons of oxygen. This is enough to meet the annual needs of 18 people."[23]

VEGETATION AS AN ENERGY SAVER

U.S. Forest Service meteorologist Gordon Heisler estimates that well-positioned trees arrayed around conventional houses can lead to energy savings of 20-25% when compared to the same house located in an unvegetated open area.[24]

VEGETATION AS AN ECONOMIC FACTOR

The American Forests organization (AmericanForests.org) has created modeling software to help communities analyze the effects of their urban forests. Results

from this model showed that tree cover in Garland, Texas, was saving the city $5.3 million a year through residential energy savings, runoff reduction, and air pollution removal.[25] In 1985, the American Forestry Association estimated that over the course of a year, an average 50-year-old urban tree would supply air conditioning worth $73, soil-erosion and stormwater control worth $75, wildlife shelter worth $75, and air-pollution control valued at $50, for a total value of $273 (in 1985 dollars). The lifetime value of the tree, compounded by 5% for 50 years was estimated at $57,151.[26] The U.S. Forest Service estimates that market values for homes are increased from 7 to 20% by the presence of trees.[27] And calculations of monetary value do not begin to address the trees' true value for enhancing quality of life in addition to property value.

VEGETATION AS A LIVING TOTEM, HISTORICAL MARKER OR MONUMENT

Plant a climate-appropriate, long-lived tree to mark a birth, wedding, graduation, or the passing of a life. Long-lived species include the native oak on the west coast of the U.S. and the desert ironwood tree or saguaro cactus in the Sonoran desert (fig. 11.27). These plants will grow with the child, relationship, career, or memories, improving life in the present and providing for the future. A marble tombstone or monument is static. A living tombtree or monument steadily grows into a more useable and enjoyable form. Any time is a good time to plant a tree, though the best time is 20 years ago, or today. See appendix 4 for more information about living monuments and green burials.

Fig. 11.27. A living totem to my brother's birth and life. When Mark Lancaster was born (45 years before this photo was taken) the saguaro he is hugging was the size of the adolescent saguaro in his right hand. We've planted similar-sized adolescents to mark my brothers' marriages and the births of their kids. The saguaros, relationships, and kids then grow up together.

VEGETATION AS STORMWATER MANAGEMENT

The resource guide *Shading our Cities* reports that USDA scientist Rowan Rowntree found vegetated areas intercept and transpire enough water to significantly modify the water budget of urban regions. He states, "in a one-inch (25-mm) rainstorm over twelve hours, the interception of rain by the canopy of the urban forest in Salt Lake City reduces surface runoff by about 11.3 million gallons (42,827,000 liters), or 17%. Most cities could count a like reduction, with the values increasing as the canopy increases. That [vegetation] allows surface-water recharge, cuts the cost of wastewater disposal, and averts the flooding and sedimentation of city streams or rivers."[28]

TREES AS AIR CONDITIONERS

The Cool Communities website quotes the USDA as saying, "The net cooling effect of a young, healthy tree is equivalent to ten, room-size air conditioners operating 20 hours a day."[29] The National Wildlife Federation notes "There are about 60 million to 200 million spaces along our city streets where trees could be planted. This translates to the potential to absorb 33 million more tons of CO_2 every year, saving $4 billion in energy costs,"[30] and helping mitigate the effect of global climate change caused by our excessive discharge of carbon dioxide into the atmosphere.

VEGETATION AS A FACTOR IN COUNTERACTING CLIMATE CHANGE

Around 80% of global warming has been caused by carbon dioxide liberated by humans burning fossil fuels, especially coal. Due to the very long life of CO_2 in the atmosphere, around 56% of all CO_2 ever released by human activity is still aloft. It is too late to avoid changes being brought on by global warming, but we still have time to implement strategies to avoid disaster.[31] The primary action must be to reduce the 1990 level of CO_2 emissions by 70% by 2050.[32]

The sooner we accomplish this, the more positive the outcome. You as an individual could achieve a 70% reduction in greenhouse gas emissions almost instantly by replacing a four-wheel-drive vehicle with a hybrid fuel car and, when possible, by carpooling, walking, and bicycling instead of driving. You can do your part to reduce greenhouse gas emissions at power plants by using less power; using more energy-efficient appliances; installing a solar-, wind-, or microhydro-power

system at home; or calling your local energy provider to purchase *renewable energy* from a green energy program.

At the same time we can plant perennial vegetation—especially trees—to draw existing carbon from the air, and sequester or bind it within their tissue. Forest and scrub vegetation across the continental 48 states can take up half a billion tons of carbon, balancing out more than a third of the emissions from U.S. cars and factories.[33] That's a huge gift, but we need to shift the balance so carbon sequestration exceeds carbon emissions. See appendix 4 online, section VII (Introduction) for resources to reduce climate change.

REAL-LIFE EXAMPLES

STREET TREE ORCHARDS— TUCSON, ARIZONA

In my hometown (average annual rainfall of 12 inches or 305 mm at elevation of 2,500 feet or 762 m) there is a collaborative effort to promote, celebrate, and enhance local food production by planting indigenous, food-bearing shade trees, then showing folks how to harvest and process the bounty. Annual events include neighborhood tree plantings, mesquite-pod grinding, and native-food feasts.

Neighborhood tree plantings focus on low-wateruse, food-producing native shade trees that provide nest sites to draw native song birds back into the urban and suburban core. Neighbors can purchase 5-gallon (20-liter) trees for at reduced prices thanks to generous subsidies from Trees for Tucson. Volunteer crews of neighborhood residents receive instruction on planting trees in water-harvesting earthworks, then plant trees along streets and sidewalks and in private yards (fig. 11.28A,B).

Fig. 11.28A. Girl Scouts planting a street tree in 1996.

Fig. 11.28B. In 2006, Chi Lancaster stands beside the velvet mesquite tree planted ten years before in fig. 11.28A. Seed pods harvested from the tree are tasty to chew on and can be ground into flour. Neighborhood cholla buds, olives, chiltepines, mesquite flour, prickly pear jam, and honey sit on the ground near the curb cut that allows street runoff to passively irrigate food-bearing plants in the right-of-way.

Within hours of planting, the neighborhood is changed for the better. More neighbors know each other, newly planted trees demonstrate community commitment, and water-harvesting earthworks are ready to fill in the next rainfall.

Six years later, trees are full and beautiful, native songbirds flourish, and the flora and fauna of the local ecosystem anchor the community's sense of place (fig. 11.28B). Within eight years of planting, tree-shaded neighborhoods are noticeably cooler than unplanted areas as tree shade starts to offset the heat-island effect caused by excessive pavement and buildings exposed to the sun.

In the Tucson area, indigenous food trees include velvet mesquite (*Prosopis velutina*), foothills palo verde (*Parkinsonia microphyllum*), blue palo verde (*Parkinsonia floridum*), and desert ironwood (*Olneya tesota*). Once established, these trees can survive on rainfall alone and will thrive within water-harvesting earthworks. Native food trees in other regions might include oak, pinyon pine, sugar maple, walnut, or date palm.

Mesquite-milling days and wild food feasts are organized in June at a local farm. June is the peak of our native bean tree harvests just before the summer rains arrive. Wild foods such as mesquite pancakes served with syrup made from the fruits of prickly pear and saguaro cacti "plant the seeds" of native foods' delicious tastes and potential within the minds and palate of the hungry public (fig. 11.29).

Fig. 11.29. Garth Mackzum feasting on mesquite pancakes with prickly pear syrup

The feast is enriched by the sale and consumption of local garden-produced corn, squash, tomatoes, and tepary beans, and cultural foods including tamales, sweet-potato pie, and pickled cholla buds. Local musicians play as folks eat and the mobile community hammermill is fired up to grind the mesquite pods brought by neighbors who harvested in early summer (fig. 11.30). Flour goes home with the harvesters so mesquite breads, cookies, tamales, and sauces can be cooked up in their kitchens.

Fig. 11.30. Mobile hammermill grinding mesquite pods into edible flour

By planting and harvesting the produce of the native ecosystem and backyard gardens, we make these foods sustainable parts of our daily experience, community/cultural identity, and food security. Mesquite pods were once a major food of the indigenous peoples of this area. Perhaps they will be a major food again, both for the indigenous people and more recent arrivals. See DesertHarvesters.org and DunbarSpringNeighborhoodForesters.org for more.

Note: See the "Watering Street Trees with Street Runoff" in the Real-Life Examples section of chapter 8 for more before-and-after photos of neighborhood tree planting. And see "Turning Flood-Control Structures Into Beautiful Water-Harvesting Amenities" in the Real-Life Examples section of chapter 2 for planting strategies appropriate for common landscapes of cohousing, condominium, and apartment complexes.

NATIVE LIVING CHRISTMAS TREES

A new place-based holiday tradition is growing in the Southwest as folks forgo solely ornamental, exotic, water-needy, coniferous Christmas trees and instead use food- or medicine-bearing, low-water-use native plants (fig. 11.31). In the low deserts, evergreen desert ironwood trees, saguaro cactus, and creosote bushes are

purchased from local nurseries and decorated for the holidays with dried ornaments from the desert such as devil's claws, yucca seed pods, and the orchid-like skins of saguaro fruit. In the high deserts, potted indigenous pinyon-nut-producing pines replace non-native pines. After the holidays these native, low-water-use plants are planted in water-harvesting earthworks in the yard or right-of-way and become long-term gifts to the community and ecosystem.

Fig. 11.31. Native food-bearing Christmas trees young (in the foreground, just before planting) and old (in the background, planted years ago). My nephew Vaughan tries to show how big the desert ironwood tree will grow, just before we plant it and the rain along the public right-of-way's footpath.

PLANTING RAIN THEN SEED TO GROW COMMUNITY FORESTS

I've had great success expanding community forests in my neighborhood even when confronted with neighbors who were into the plantings, but not into buying them or watering them to get them established. First we plant rain in locations where trees and understory are desired and where runon is available, then we collect seed from desired multi-use native plants already growing nearby, then we plant the seed within the earthworks *at the beginning of the rainy season*. The newly germinated seeds then send down roots that are very deep, wide, and drought-resilient because they have never been hemmed in by a pot. We typically walk away after planting the seed—never irrigating the growing plants because the well-placed earthworks do the watering for us! See DunbarSpringNeighborhoodForesters.org for more.

PLANTING AN URBAN FOREST TO MANAGE A CITY AS AN ECOSYSTEM – LOS ANGELES, CALIFORNIA

At age 15, Andy Lipkis felt the power of tree planting. During summer camp, he helped plant smog-resistant cedar and pine trees in dying sections of the Santa Monica Mountain forests. The forests surrounded by Los Angeles were dying from excessive air pollution. The plantings succeeded and life again flourished. Seeing the forest's transformation, thanks in part to his efforts, gave Andy great strength. He wanted other kids to experience this too. So, three years later, in 1973, Andy founded the nonprofit organization TreePeople to undertake tree planting to save more of the Santa Monica Mountain forests, and to green the city of Los Angeles as well. Just over 1,000 trees were planted in the first project Andy organized.

Since then, Tree-People has grown to 55 employees and thousands of citizen-volunteers who have planted over two million trees in 30 years. And they plan to plant a million more, potentially increasing the city's existing tree canopy by nearly 60%. People of all ages are trained to plant and care for trees as part of myriad programs. These include distributing free fruit trees to low-income neighborhoods; replacing large swaths of paved school campuses with trees and turf planted by students, teachers, and parents; and putting on free workshops preparing citizen-volunteer foresters to plant in yards, neighborhoods, parks, and forests. These efforts have led to cleaner air, increased shade, reduced flooding, energy savings, a more livable city, and a populace engaged as stewards of their homesites, community lands, and watershed.

And now, as you can read in this book's foreword, the efforts of Andy, TreePeople, and the city of Los Angeles have extended to "planting the rain" as

they plant the trees. Andy and TreePeople did this by leveraging the reallocation of money earmarked for multimillion-dollar flood-control projects and sewage treatment plants designed to drain the city's watershed of much of its 14.7 inches (373 mm) of average annual rainfall, to instead create a diverse array of multiuse *greenfrastructure* that hydrates the watershed. The greenfrastructure consists of water-harvesting strategies combined with urban-forestry projects on private property, in parks, on school grounds, along streets, and within parking lots to naturally capture, filter, infiltrate, and reuse stormwater throughout the city's watersheds.

With each example and each success the city moves closer to sustainability, the health of its ecosystem improves, and the community is strengthened as people get to know one another and work together. It's a biologically based, integrated approach that began with Andy's teenage vision sparked by planting trees.

Perhaps that's why TreePeople focuses so much energy on kids' programs. They've resulted in tens of thousands of L.A.'s kids planting trees and participating in the water-harvesting transformation of their schools and neighborhoods—empowering them to envision and realize whole new acts of positive change that will inspire tens of thousands more.

For more information see TreePeople.org.

CHAPTER 12

Harvesting Greywater and Other On-Site "Wastes" Turned Resources

The society which scorns excellence in plumbing as a humble activity and tolerates shoddiness in philosophy because it is an exalted activity will have neither good plumbing nor good philosophy; neither its pipes nor its theories will hold water.

—John W. Gardner, 1991

The previous chapters illustrated how to create and plant water-harvesting earthworks, the *foundations* of sustainable landscapes. Earthworks passively harvest our primary water source—direct rainfall and resultant runoff—into bowl-like shapes in living soil to help support multiuse plants. This chapter shows how to maximize the potential of earthworks near homes and buildings by using them to harvest and recycle secondary water sources—especially in times of no rain. Secondary water sources include greywater from the drains of clothes washers, bathtubs, showers, and sinks (fig. 12.1); *clearwater* discharge water from reverse-osmosis water filters; bleed-off water from evaporative coolers (fig. 12.2); and air conditioning condensate—atmospheric water that condenses on the cold coil of an air conditioning unit (fig. 12.3).

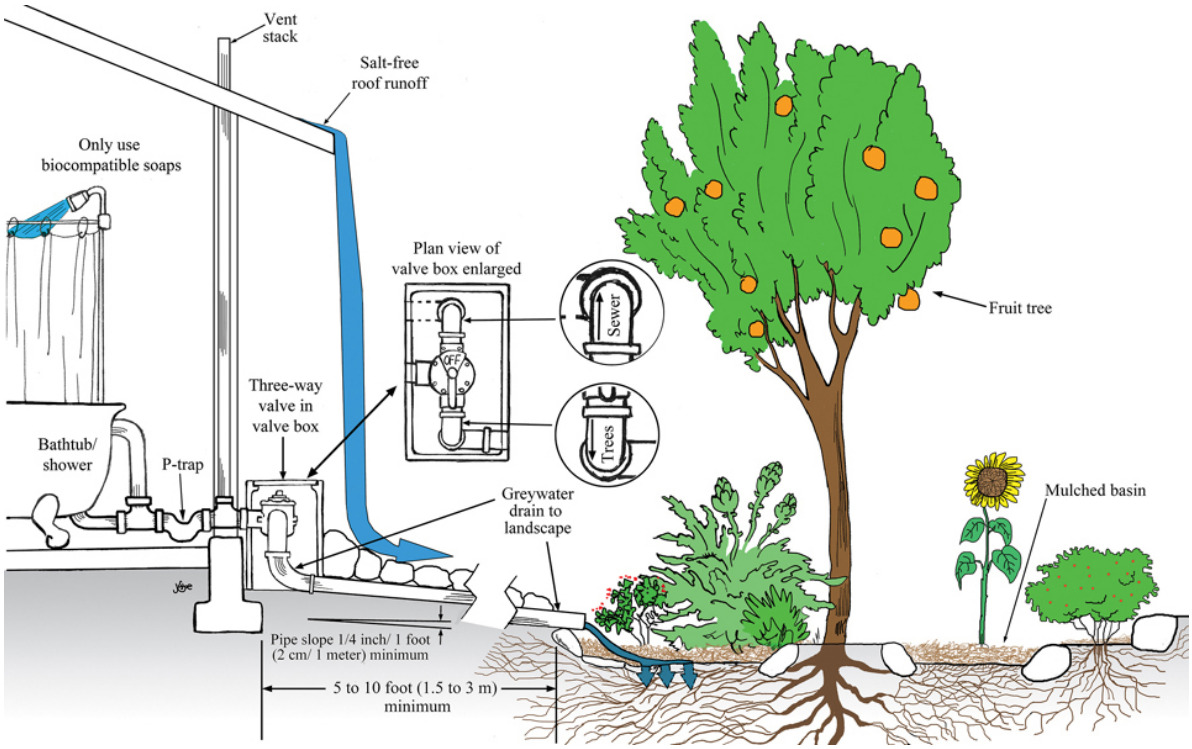


Fig 12.1. A bathtub/shower greywater "spring" directs drain water to a well-mulched and vegetated infiltration basin. Note P-trap and vent stack between interior drain and exterior greywater outlet, which prevents potential entry of odor and insects into house. A three-way valve (downstream of the P-trap and vent) in a valve box allows for distribution of greywater to either the landscape or the sewer. The end of the greywater pipe discharges 2 to 3 inches (5 to 8 cm) above the mulch in the basin to prevent roots from growing into the pipe and solids from backing up and clogging the pipe. Greywater immediately infiltrates beneath the surface of the mulch into the soil of level-bottomed basins to be used by plants.

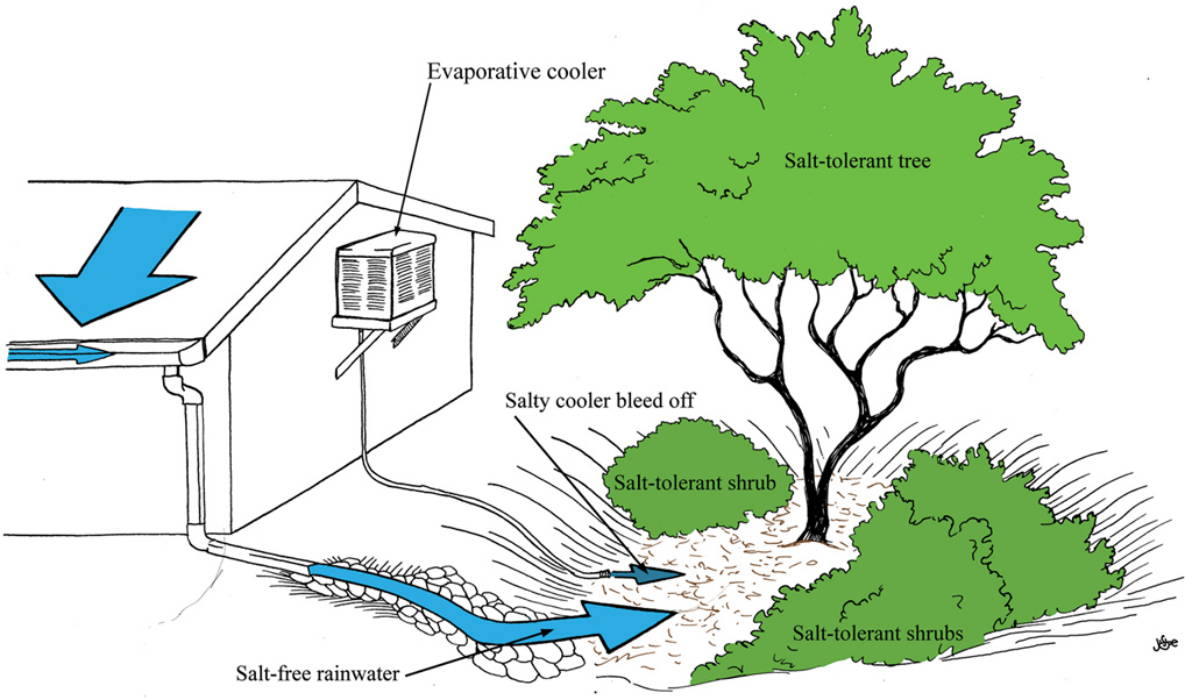


Fig. 12.2. An evaporative cooler "spring" irrigating a salt-tolerant tree and shrubs. The overflow drain hose from an evaporative cooler directs bleed-off water to a sunken, mulched basin. The household cooler bleed-off discharge rate can range from about 1 gal/hour (4 liters/hour) to 5 gal/hour (19 liters/hour). Cooler bleed-off water is high in salt, so associated plantings must be salt-tolerant and occasionally flushed with salt-free rainwater to remove accumulated salts from their root zones. Screwbean mesquite tree (*Prosopis pubescens*), four-wing saltbush (*Atriplex canescens*), and native wolfberry (*Lycium fremontii*) are used here. As the tree grows tall enough to shade the cooler and building, the cooler's efficiency increases

Fig. 12.3. A home air conditioner's condensate wastefully drains to bare dirt in dry Tucson, Arizona. Instead, direct the flow of condensate water to mulched and vegetated basins where this high-quality, salt-free water can help dilute salts that accumulate from harvested greywater and evaporative-cooler bleed off. In hot dry times condensate volume is low, but condensate volume can be significant in humid climates or humid seasons (box 12.9). Commercial and

industrial air conditioners create a vast untapped source of high quality water that too often flows wastefully to the sewer.

Recycling secondary water sources within earthworks will enable you to support a lush landscape year round, while reducing or eliminating irrigation with drinking water delivered from municipal supplies or wells. You'll turn "waste" water into "resource" water producing shade, food, cleaner air, wildlife habitat, and other benefits around homes and other buildings.

Throughout this chapter you will be guided through natural patterns that inform important design principles. Use these design principles to create efficient, safe, cost-effective, life-sustaining systems; to effectively assess your site's greywater-harvesting potential; and to choose, implement, and evolve the best options for harvesting multiple on-site waters.

PATTERN: **The volume of available fresh water on this planet is finite. Of all the water on Earth, fresh water accounts for only 3%, and most is locked up in ice and glaciers (75%) or in groundwater more than 2,600 feet (800 m) deep (13.5%).**[1] **The planet does not run out of circulating fresh water because the Earth's hydrologic cycle uses and naturally filters water again and again, cycling it—often through myriad life forms—to continually renew water quality and support the maximum diversity of life and resources. Within the natural system there is no waste, no pollution, no importation of energy, and no utility bills.** But the current unnatural contamination of our planet's waters through human-caused pollution is stressing the natural system.

PRINCIPLE: Strive to mimic and synergize with the planet's natural hydrologic cycle.

Set up your earthworks to passively harvest and cycle multiple free on-site "waste" waters through living filters to transform them into "resource" waters.

Don't pollute our planet's waters.

Read on to see how the combined cycling of rainwater and "wastewater" has created fire-resistant landscapes within fire-ravaged land, and has grown an educational oasis on a university campus. See how neighbors forming "greywater laundromats" build community and grow fruit, and how homes built with greywater systems and composting toilets productively harvest and recycle "wastewater" and "waste" within thriving landscapes.

All greywater harvesting options discussed or referenced in this chapter are safe, easy, convenient, and affordable.

WHAT IS GREYWATER HARVESTING?

Greywater is once-used "wastewater" originating from a clothes washer, bathtub, shower, sink, or drinking fountain. Wastewater from flushed toilets is called *blackwater* (box 12.1). Wastewater that originates from a kitchen sink and dishwasher contains higher levels of organic solids and coliform bacteria than other grey-water sources, so some regulators consider these water streams blackwater as well, but I prefer Art Ludwig's classification of *dark grey water*.[2]

Box 12.1. What's the Most Dangerous Thing We Can Do with Greywater? Turn it into Blackwater.

Blackwater is water found in septic tanks or sewage flushed from a toilet, and it is more difficult to safely treat or reuse than the much more benign greywater. Don't mix greywater and black-water, because once you do it all becomes black-water. Similarly, don't mix greywater with dark greywater from a kitchen sink, since this will make it all dark greywater. And don't let greywater sit in a tank, because that can lead to the water turning foul and stinky.

Thanks to David Eisenberg, Executive Director of the Development Center for Appropriate Technology for posing this question and what it informs.

Clearwater is wastewater that does not have added solids such as discharge water from reverse-osmosis water filters and the condensate formed by air-conditioning and refrigerator units. Clearwater can be harvested as greywater, or harvested separately using simpler runs of small diameter tubing.

The original source of water, which after one use becomes greywater, could be harvested rainwater, municipal/well water, or a combination of these.

Unlike blackwater, which has to be discharged into the sewer, greywater can be safely treated and recycled/reused on site. *Greywater harvesting* is the practice of directing greywater to the primary root zone (top 2 feet or 0.6 m of the soil) of perennial plants to help grow beautiful and productive landscapes while achieving wastewater treatment without using energy or chemicals.[3] Plants and microorganisms in the soil consume and filter the organic nutrients and bacteria found in greywater, treat it naturally, then return clean water to the water cycle (figs 12.4A, B).

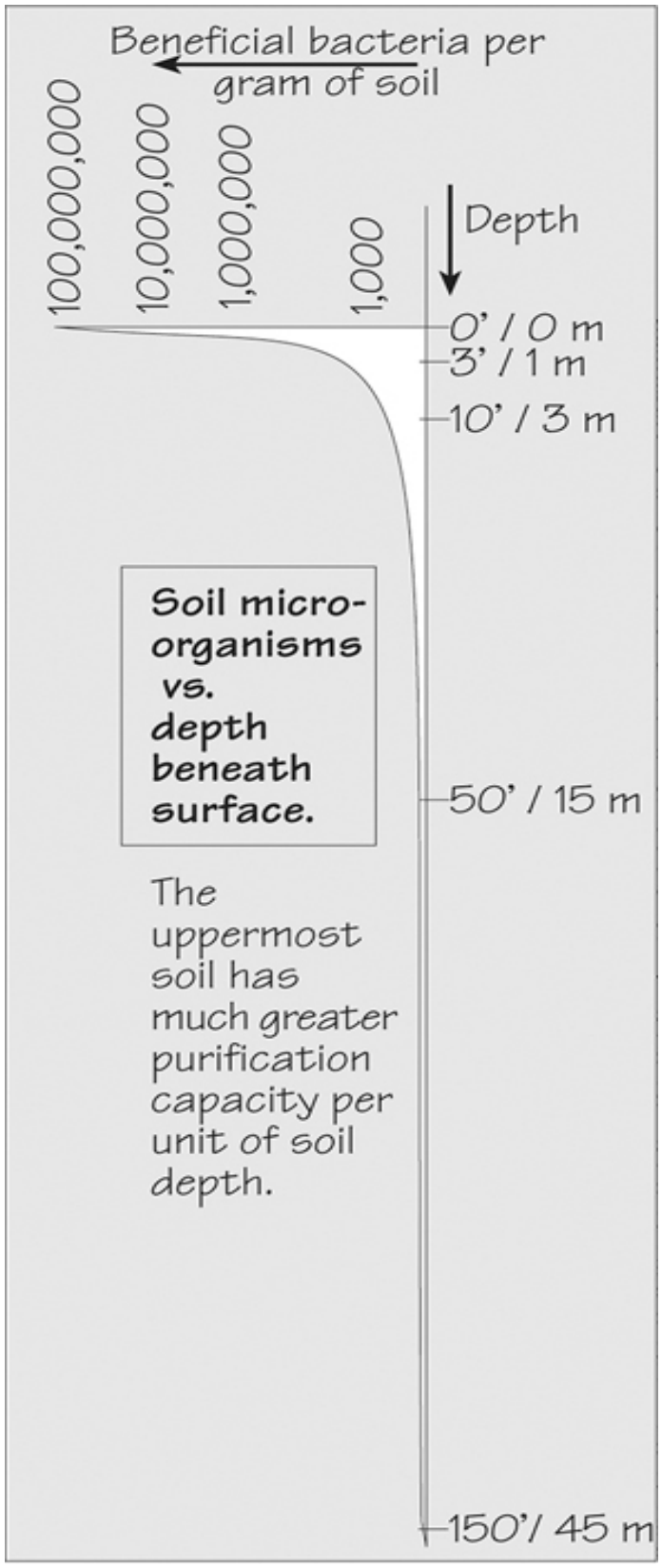

Beneficial bacteria per gram of soil
100,000,000
10,000,000
1,000,000
1,000
Depth
0' / 0 m
3' / 1 m
10' / 3 m
Soil micro-organisms vs. depth beneath surface.
50' / 15 m
The uppermost soil has much greater purification capacity per unit of soil depth.
150'/ 45 m

Fig. 12.4A. Collaborate with soil life. The higher in the soil profile you discharge greywater, the more beneficial microorganisms there are to naturally filter or bioremediate the water. Reproduced with permission from the *Builder's Greywater Guide* by Art Ludwig.

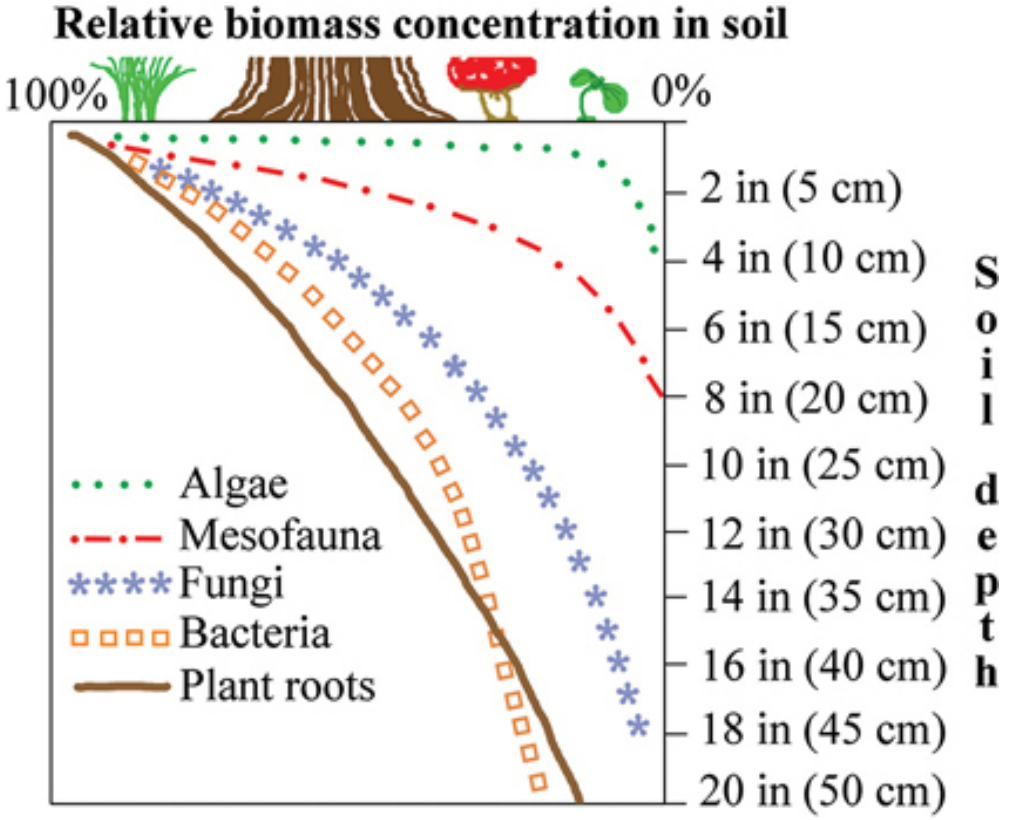


Fig. 12.4B. Collaborate with soil life. The higher in the soil profile you discharge greywater, the greater the number of roots and other life forms there are to utilize and naturally filter the water. Adapted from the *Nature and Properties of Soils* by Nyle C. Brady and Ray R. Weil.

Greywater harvesting is a great way to reduce potable water use and implement the sustainable hierarchy of water use, where:

- Rainwater is your landscape's *primary* water source,
- Greywater is the *secondary* water source, and
- Municipal/well drinking water is strictly a *supplementary water* source only used in times of need.

PATTERN: Greywater is available even in dry times (as long as you are home sending water down the drain).

PRINCIPLE: Don't plant any higher-water-use vegetation needing dry season irrigation (such as exotic fruit trees), until you've first "planted" both rainwater and greywater to support those plants.

Plant higher-water-use plantings in *wetter oasis zones* close to homes/buildings that generate greywater and rainwater runoff (figs. 1.11, 1.12).

Greywater is free, stays on site, and consumes no energy if it is distributed using gravity. It is also abundantly produced by U.S. households (see boxes 12.2, 12.6).

Box 12.2. How Much Greywater Does a Household Produce?

Based on typical water consumption in the United States, a single person produces up to 40 gallons (151 liters) of greywater per day, while a family produces around 140 gallons (530 liters) per day. If all sources of residential greywater were recycled on site, this family would have 51,000 gallons (193,100 liters) of water per year to irrigate plants with in their landscape.[4]

See boxes 12.6, 12.8, and 12.9 to estimate how much greywater you produce.

Note: Typical water consumption in the U.S. is very high compared to the rest of the world, so practicing conservation measures in addition to greywater reuse would be wise. (See boxes 12.6, 12.8, 12.9 for more information on water usage and conservation.)

Reclaimed water consists of greywater and black-water that is drained off site where it is mechanically and chemically treated, then is pumped to selected destinations for reuse. Reclaimed water is expensive and energy intensive. It is typically used for large-scale irrigation at ball fields, golf courses, and parks, but is also piped to residential areas in some cities.

Drinking water can come from a pristine spring, creek, or well, though more often these days it is water that has been filtered and treated (often mechanically and/or chemically) to meet drinking water standards, and then pumped/delivered via a means that maintains that water quality—thus it often has substantial financial and water-energy-carbon costs (see Volume 1, appendix 9). The water delivered to our homes via municipal systems is drinking water—including the water distributed to our toilets, garden hoses, and irrigation systems.

For home- and garden-scale landscape irrigation, on-site greywater reuse is far more economical and energy efficient than using pure drinking water or reclaimed water. People save money managing their own systems and reduce the community's "need" to unsustainably over pump aquifers, rivers, or creeks; import water; and treat and deliver expensive reclaimed water. The key is to start harvesting *greywater high in your watershed* just as you do with rainwater, and to

treat greywater within the living filters of topsoil (see next section, Collaborating with Living Filters and Living Pumps).

Greywater harvesting is legal in many parts of the U.S. and elsewhere, and is being actively promoted with financial incentives in some locations (see box 12.3, box 12.4).

Box 12.3. The Legality of Greywater Use

Regulations in Arizona and New Mexico currently set the standard for encouraging greywater use in the United States, and have paved the way for many other states to legalize and promote the use of greywater. No greywater permits (though a standard plumbing permit may be needed), inspections, or fees are required for household systems that follow basic guidelines and have greywater flows that do not exceed 400 gallons (1,514 liters) per day in Arizona[5] or 250 gallons (946 liters) per day in New Mexico.[6]

For more, see this chapter's Real-Life Examples and search "Greywater Laws" at HarvestingRainwater.com. Call local authorities for regulations in your area. See the Greywater Policy Center at OasisDesign.net, which lists regulations for many states in the U.S. In areas that have not yet legalized or encouraged greywater harvesting, share examples from areas where greywater harvesting is legal and encourage your local officials and policy makers to allow greywater harvesting.

Box 12.4. Greywater-Harvesting Incentives

In Tucson, Arizona, homeowners can take a free two-hour greywater-harvesting class to qualify for a rebate of up to $1,000 for installing a permanent greywater-harvesting system.

For more info on this and other incentives, search "water-harvesting incentives" at HarvestingRainwater.com.

COLLABORATING WITH LIVING FILTERS AND LIVING PUMPS

You may have noticed that water and life are colored in this chapter's illustrations, but not plumbing. Why do you think this is?

Well, it's to highlight the living elements, the ecology of the system—because life is the core of the system, and life needs water. That's why it works. Enhance water and life and you enhance the system.

The potential of the living filters is represented in figs. 12.4A, B. The living pumps of vegetation, collaborating with mycorrhizal fungi and beneficial bacteria in the soil, freely redistribute and transform on-site resource waters into other useful forms like fruit, beauty, and shelter. The plants' roots fuse with the hair-like "roots" or hyphae of beneficial fungi and bacteria in the soil to increase the overall

capacity of roots up to hundreds of times, thereby dramatically enhancing the ability of vegetation to utilize water and nutrients (fig. 12.5).[7]

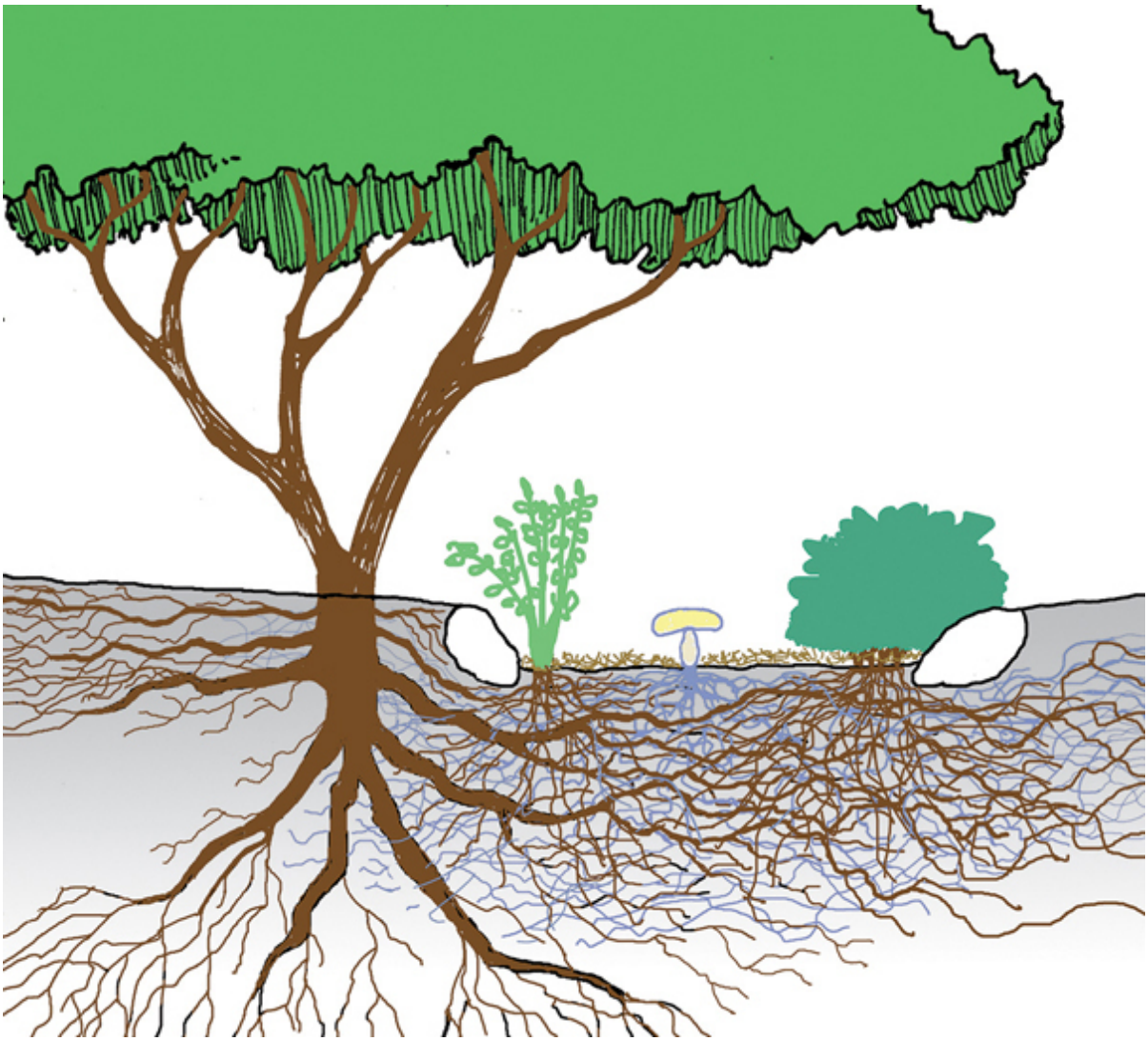


Fig. 12.5. Most mushroom fungi are mycorrhizal, meaning they have symbiotic relationships with trees and other vegetation. The fungi's hyphae or roots fuse with the tree rootlets. The tree then feeds the fungus sugars and the fungus brings water and nutrients to the tree. Trees grow much slower without fungal symbionts.

PATTERN: Microorganisms in healthy soil serve as living filters, sequester carbon, and enhance soil fertility. Their numbers and diversity are greatest in the upper layers of the soil (figs. 12.4A, B), and having sufficient soil moisture enhances their work.

PRINCIPLE: Collaborate with soil life by distributing greywater and other on-site waters in the uppermost layers of the soil to maximize the health of soil microorganisms and make optimal-use of the water. Reinvest on-site organic matter, such as leaf drop as mulch or compost atop the soil, rather than raking it away. Avoid using biocides and herbicides on your soil. Avoid using household products such as chlorinated bleach that could make their way into greywater and are toxic to soil life. Do not use plastic mulch, which dehydrates the soil and kills soil life. Encourage the growth of vegetation and other beneficial life.

WHERE GREYWATER IS USED

Greywater can be safely and effectively used if a few basic rules are followed. The best approach to safe greywater use will depend on your site's characteristics and the quality and quantity of greywater available. An overview of these considerations is provided below. More in-depth information is provided later in this chapter.

GREYWATER CAUTIONS AND SOLUTIONS

There has never been a documented case of greywater-transmitted illness in the United States.[8] Nonetheless, for safety, success, and aesthetics, be aware of the following cautions and simple solutions (See *The New Create an Oasis with Greywater* for more information):

• CAUTION: *Greywater may contain infectious organisms washed from your body, clothes, or food.*

SOLUTION: Do not drink greywater. Avoid direct contact with greywater by discharging it where it will rapidly infiltrate into mulched and vegetated soil. Label all greywater lines. Wear gloves when working in greywater-irrigated soils, and wash your hands when work is done.[9]

• CAUTION: *Greywater may contaminate the surface of fruits or vegetables it comes in contact with.*

SOLUTION: Do not allow greywater to come into contact with uncooked edible portions of food crops. Do not distribute greywater through sprinklers. Avoid using greywater to irrigate root crops or low-growing salad greens that touch irrigated soil.[10] Though a plant's roots and stem are in contact with greywater, if the fruits or vegetables growing on that plant do not come into

contact with greywater they will be fine to eat (e.g., oranges on a tree, tomatoes on a trellised vine, and artichokes cut well above ground). Do not consume fallen fruits or raw vegetables that come into direct contact with greywater-irrigated soil.

• CAUTION: *Greywater tanks smell.*

SOLUTION: As a general strategy, do not store greywater in a tank. However, if you do store it in a tank, do not store it for more than 24 hours. Microorganisms can grow and reproduce in the undigested organic matter within it.[11, 12] Instead, discharge greywater directly into healthy topsoil where the water and nutrients will be used before bacteria multiply.

• CAUTION: *Soil waterlogged with greywater can smell, attract mosquitoes, and suffocate plants.*

SOLUTION: Do not concentrate greywater in an area where it could pool and waterlog soil for more than 24 hours, because this can cause the soil to become anaerobic (lacking oxygen). Instead, disperse greywater intermittently to different areas in the landscape so each area fully drains and aerates between waterings, keeping soil aerobic (having oxygen).[13] Maximize quick infiltration of greywater by mulching basins. Plant with water-tolerant perennial vegetation placed in its ideal rain garden zone/microclimate (see chapter 11, and appendix 4 of Volume 1). Or play it safe and plant on basin bank terraces or pedestals that drain well so the root crown at the base of plants is kept relatively high and dry.

• CAUTION: *Greywater irrigation could seal clayey fine-grained soils with soaps or fats and increase salt buildup in soil, adversely affecting plants.*

SOLUTION: Mulch soil to create a coarse filter that prevents soil from clogging with soaps or fats. The mulch also minimizes evaporation that would otherwise leave salts behind, and reduces the erosive impact of greywater surges. Keep kitchen food scraps, fats, and oils out of greywater streams—compost them instead (fig. 12.33). Use low-salt, greywater-compatible soaps and detergents (see box 12.5). Plant areas irrigated with greywater with salt-tolerant vegetation. Flush greywater-irrigated areas with a good dose of salt-free rainwater at least once a year.

Box 12.5. Soaps, Detergents, and Greywater

Cleaning products labeled "biodegradable" or "natural" or even "eco-friendly" may not be greywater-compatible—meaning suitable for the plants and soils in your greywater-irrigated landscape.

GREYWATER-COMPATIBLE PRODUCTS

I prefer to use Oasis brand or Bio-Pac concentrated liquid laundry detergent and dishwashing soap (see Biopac.com); both are greywater compatible. I dilute 1 part Oasis brand dishwashing soap with 8 parts water for hand and body soap. For shampoo, I currently use Alaffia brand's Everyday Shea Shampoo. But I always scan the ingredients of any soap or detergent before buying to be sure there are no sodium products, since companies often change their products' ingredients, and some products that were good for me and greywater irrigation in the past no longer are.

Traditional liquid soaps made from potassium-based ingredients, such as most Dr. Bronner's liquid soaps and handcrafted liquid soaps, are greywater compatible as long as they don't contain harmful additives such as lye or sodium salts. You can contact soap makers and ask about their ingredients.

PRODUCTS AND INGREDIENTS TO AVOID

- Harsh chemicals such as chlorine and drain cleaners
- Bleaches and fabric softeners
- Detergents with whiteners, softeners, and enzymes
- Bar soaps and powdered laundry detergents that typically use sodium-based products as filler material. Sodium salts can harm plants and soils. Accumulation of salts is of special concern in drylands where soils tend to be alkaline and naturally high in salts. It is wise to occasionally flush dryland soils with rainwater or other non-salty water.
- Borax and other cleansers and products made with boron. Boron is needed by plants, but only in extremely small amounts.
- Soaps and detergents with the following ingredients: peroxygen, sodium perborate, sodium trypochlorite, petroleum distillate, alkylbenzene, salt
- Disinfectants
- Bath salts and bubble baths, which are also high in sodium

The above list of products and ingredients was primarily compiled from State of California, Department of Water Resources publication *Graywater Guide: Using Graywater in Your Landscape*.

For more information on soaps and detergents, recommended brands, and laundry and cleaning tips, search and see "Greywater Harvesting" at HarvestingRainwater.com.

- CAUTION: *Insects or vermin may try to enter a home through a greywater pipe.* SOLUTION: Install a conventional P-trap and vent between your house drains and grey-water pipe outlets. Hire a plumber and/or see a plumbing book for P-trap and vent installation. (Search HarvestingRainwater.com for "Plumbing for Homeowners" for a free guide). Just as P-traps and vents keep gases and vermin from entering your home through sewer pipes, they also keep insects and vermin from entering your home through greywater pipes in your yard. Avoid attracting insects and vermin into your plumbing in the first

place by composting food scraps, fats, and oils instead of disposing of them in a sink garbage disposal.

- CAUTION: *Chemicals sent down the drain may contaminate plants and soil.*
  SOLUTION: Do not use household drains as waste disposal systems to "throw something away." There is no "away." Instead, consider drains as conduits to the natural world. Don't buy or use toxic chemicals. Avoid products containing boron or chlorine bleach. Do not clean car parts, wash oily rags, or dispose of toxic solutions such as paint thinner in greywater systems. Use environmentally benign cleaning agents (see box 12.5; and the "Greywater Harvesting" page at HarvestingRainwater.com). If you can't avoid contaminating water, divert the contaminated water to the sewer or septic system (figs. 12.7B-12.11, 12.29 and 12.30) and reevaluate your lifestyle to prevent such contamination in the future.

- CAUTION: *A massive week-long family gathering could overload a system designed for just a few people.*
  SOLUTION: Size your system to handle larger-than-average volumes (see this chapter's Developing a Gravity-fed Greywater System section) or divert the greywater to the sewer or septic system for the week (see Greywater Harvesting Stub-Outs section).[14]

- CAUTION: *Greywater could mingle with, and contaminate, surface water.*
  SOLUTION: Do not allow greywater to run off your property or to mingle with surface water. Discharge greywater on site below ground or within mulched infiltration basins, and contain it at these discharge points. Do not apply greywater to saturated soils.[15]

SITE CONSIDERATIONS

PATTERN: Gravity is free and never breaks down, while pumps are expensive, need power, and do break down.

PRINCIPLE: Whenever possible, design your system to use gravity to move greywater (and other waters) rather than mechanical pumps.

The systems described here use gravity flow to irrigate areas of the site that are lower in elevation than the home's greywater sources. To make gravity-fed distribution possible, the greywater drain pipe must have a minimum 2% slope,

dropping 1/4 inch per linear foot (2 cm drop per linear meter) from its source to its outlet in the top 2 feet (0.6 m) of soil—the primary root zone of plants. Greywater pipe can slope more than 2%, but not less. The higher the elevation where greywater exits the house the better, allowing gravity to deliver greywater to lower and more distant land areas while maintaining the minimum pipe slope necessary for gravity-fed distribution. To irrigate areas that are higher in elevation than your greywater source, consider moving your greywater source (for example, setting up an outdoor shower higher than the area to be irrigated) or search "laundry to landscape" online to find systems that use your washing machine's pump to pump grey-water up to 5 feet (1.5 m) above the washer.

I recommend discharging greywater into mulched, rainwater-harvesting earthworks within the site's wetter oasis zone, as described in chapter 1 (figs. 1.9, 1.11 and 1.12). This zone is positioned around gathering spots like patios, front porches, and paths, generally within 30 feet (9 m) of your home, though at some sites the slope and greywater volume may make it necessary to discharge greywater beyond this distance. Concentrating greywater in this oasis zone minimizes greywater pipe length and keeps plants that need more water and care closer to people, where the plants can be easily tended and used. However, in most cases, greywater infiltration basins should be no closer than 5 to 10 feet (1.5 to 3 m) from a building to prevent soil saturation around the building's foundation.

Limit the planting of high- and medium-water-use plants such as exotic fruit-bearing trees, shrubs, and vines to the wetter oasis zone. Some medium-wateruse plantings can go to the drier oasis zone if there is sufficient water. Only low-water-use plants should be placed outside oasis zones. Using this planting pattern, exotic plants get convenient access to "exotic" greywater and supplemental municipal/well water, in addition to "native" rainwater and runoff. Low-water-use plants—primarily natives—located outside the oasis zone are the only plants that subsist entirely on native rainwater and runoff, once the plants are established. These native plants can be enhanced with additional water-harvesting earthworks where appropriate.

Soil infiltration rates are an important consideration in designing greywater systems. In extremely porous soils, greywater could rapidly drain past the plant root zone, so these soils require special adaptations such as adding compost or other water-holding organic matter. If you are harvesting greywater in soils with insufficient percolation, greywater could pool excessively on the surface. In this

case, special adaptations could include increasing the amount of organic matter in the soil, mulching the surface with organic matter, planting living pumps of vegetation, and additional strategies described in the paragraph below. (See the Conceptualizing and Planning section later in this chapter to ensure your system is sized to adequately infiltrate all incoming greywater).

Use appropriate design strategies at sites with very small yards to avoid overloading the soil with infiltrating greywater. Strategies include limiting the number of greywater sources that drain to the yard, distributing greywater to multiple endpoints (fig. 12.12 branched drain), and/or installing a diverter valve or additional drain option to divert greywater flow to sewer or septic if soil becomes saturated (figs. 12.7B - 12.11 for sink, shower, or tub and figs. 12.29 and 12.30 in this chapter's Variations section for washing machines).

Infiltration basins for greywater and rainwater should not be constructed in drainages, above septic leach fields, or within 5 feet (1.5 m) of the top of seasonally high water tables. If you have a well, do not discharge greywater any closer to the well than county regulations would allow a septic tank leach field to be installed.[16]

Greywater use is not recommended during very wet seasons when soils are waterlogged (see figs. 12.7B to 12.11 for seasonal diversion options). Though it can still work in cold seasons when soils are frozen, but daytime temperatures (and temperature of grey-water leaving house) are above freezing. For greywater reuse within greenhouses (fig. 12.6) see *Water from the Sky* by Michael Reynolds.

Fig. 12.6. Harvesting greywater in a greenhouse in cold climate. Sink water drains to the adjoining planting bed to irrigate bananas and more at the Earthship Visitors Center in Taos, New Mexico.

QUANTITY, QUALITY, AVAILABILITY, AND ACCESSIBILITY CONSIDERATIONS OF GREYWATER AND OTHER FREE ON-SITE WATERS

Inventory all the potential free on-site waters you can harvest. Then assess their quantity using boxes 12.6, 8, and 9, and the calculations appendix for rainwater

Box 12.6. Per Capita Indoor Water Use for Average (Non-Conserving) American

Fixture	Average Volume/Use	Average Frequency	Average Use/Person/Day	Average Use/Person/Week	Average Use/Person/Year
Washing Machine	40.9 gal/load (155.0 liters/load)	0.37 loads/day (2.52 loads/week)	15.0 gal (56.8 liters)	105.0 gal (398.0 liters)	5,475.0 gal (20,750.0 liters)
Shower	17.2 gal (65.2 liters) The average shower was 8.2 minutes with a flow rate of 2.22 gal/minute (8.4 liters/minute)	0.67 showers/day (4.69 showers/week)	11.6 gal (44.0 liters)	81.2 gal (307.7 liters)	4,234.0 gal (16,046.9 liters)
Bathroom Faucet	Data Not Available	Data Not Available	3.4 gal* (12.9 liters)	23.8 gal (90.2 liters)	1,241.0 gal (4,703.4 liters)
Bathtub	24.0 gal (91.0 liters)	0.05 baths/day (Most Americans take showers instead of baths)	1.2 gal (4.5 liters)	8.4 gal (31.8 liters)	438.0 gal (1,660.0 liters)
TOTALS			31.2 gal (118.2 liters)	218.4 gal (827.7 liters)	11,388.0 gal (43,160.5 liters)

Figures for average volume/use, average frequency, and average use/person/day are from www.h2ouse.org, except for bathroom faucets. The original source of data is *Residential End Uses of Water* by P.W. Mayer, W.B. DeOreo, E. Opitz, J. Kiefer, B. Dziegielewski, W. Davis, and J.O. Nelson, a study sponsored and published by the American Water Works Association Research Foundation, Denver, Colorado in 1999. Water use was measured in 1,200 households in ten U.S. and two Canadian cities.

*Source of average American daily use estimate for bathroom faucet: http://www.watersavertech.com/Aquacraft_Savings_Report.pdf.

Box 12.8. Estimates of Personal Indoor Water Use with Efficient Fixtures and Water-Conserving Habits

Fixture	Factors Affecting Volume/Use	Frequency and Volume Assumptions	Use/Person/Day	Use/Person/ Week	Use/Person/Year
Efficient Washing Machine	Volume per use affected by washer efficiency, washer capacity, and adjustability of water levels. Efficient washers available in U.S. generally use 18 to 25 gal/load* (68 to 95 liters/load). Some use only 10 gal/load (37.9 liters/load). Capacities range from 1.6 to 3.8 ft^3* (0.045 to 0.108 m^3).	Average U.S. frequency: 0.37 loads/day (2.52 loads/week) (see box 12.6). Volume per load: 20 gal (75.8 liters/load)	7.4 gal (25.0 liters)	51.8 gal (175.1 liters)	2,701.0 gal (9,130.1 liters)
Shower	Volume per use affected by showerhead type, shower length, water line pressure, and the size valve is opened to. Low flow showerheads range from 1.5 to 2.5 gal/min* (5.7 to 9.5 liters/min). Ultra low flow showerheads range from 0.8 to 1.5 gal/min (3.0 to 5.7 liters/min).	Assumed average U.S. frequency: 0.67 showers/day (4.69 showers per week) (see box 12.6) Volume per use: 5 minutes/shower assuming flow rate 1.8 gal/min (6.8 liters/min) for total 9 gal/shower (34.1 liters)	6.0 gal (22.7 liters)	42.0 gal (159.2 liters)	2,190.0 gal (8,300.1 liters)
Bathroom Sink	Volume per minute affected by aerator type at faucet outlet, size valve is opened to, and length of time faucet is on during sink use. Faucets with an attached low flow aerator range between 0.5 to 1.5 gal/min (1.9 to 5.7 liters/min).	Assumptions: faucet turned off part of time during sink use; low flow aerator is installed. (Assuming 8 uses/day, 15 sec/use, and 1.0 gal/min (3.8 liter/min) aerator	2.0 gal (7.6 liters)	14.0 gal (53.1 liters)	730.0 gal (2,766.7 liters)
Bath	Americans typically take showers instead of baths. This estimate assumes baths typically used for washing children use low volume of water for safety reasons, and occasional use by adults who want full bath for therapeutic value.	Assumed average U.S. frequency 0.05 baths/day; volume 24 gal/use (91.0 liters) (see box 12.5)	1.2 gal (4.5 liters)	8.4 gal (31.8 liters)	438.0 gal (1,660.0 liters)
TOTALS			15.8 gal (59.9 liters)	110.6 gal (419.2 liters)	6,059 gal (21,856.9 liters)

* gal = gallons, ft^3= cubic feet, gal/min = gallons per minute

Use rates estimates based on the following sources:
www.fypower.org/res/tools/products_results.html?id=100122;
www.energystar.gov/index.cfm?c=clotheswash.pr_clothes_washers;
www.cee1.org/resid/seha/rwsh/rwsh-main.php3;
www.fypower.org/res/tools/products_results.html?id=100160;
www.watersavertech.com/Aquacraft_Savings_Report.pdf;
www.watersaver.org/indoorwateruse.asp;
www.eere.energy.gov/consumer/your_home/water_heating/index.cfm/mytopic=13050

- High efficiency washing machines cut energy and water use by half or more. Efficient machines use very little detergent (e.g.: 2 Tablespoons [30 cubic cm] of liquid detergent fo a washer with a 2.65 ft^3 [0.075 m^3] capacity). Horizontal axis (front loaders) are the most efficient.

- To estimate your showerhead's flow rate hold a gallon container under the showerhead ar record the time it takes to fill in seconds. The bucket will get heavy (8.5 lbs or 3.8 kg) so

you may want to put it on a step ladder. Then divide 60 by the seconds of fill time to calculate flow rate in units of gallons/minute. Example: If it takes 30 seconds to fill: 60 ÷ 3 = 2 gallons per minute (7.5 liters per minute). Since 1992, flow rates for faucets and showerheads made in the U.S. must be 2.5 gallons per minute or less at 80 pounds per square inch (9.5 liters per minute or less at 552 kilopascals).

Box 12.9 Estimates of Discharge Volumes from Household Evaporative Coolers, Air Conditioners, and Reverse-Osmosis Filters

Water Source	Example Discharge Rates	Factors Affecting Discharge Volume	Water Quality	Compatible Vegetation
Evaporative-Cooler Bleed-off	Evaporative coolers are most effective in high-temperature, low-relative-humidity conditions. Example discharge in dry conditions of Phoenix, Arizona: Cooler bleed-off discharge is 1 to 5 gal/hour* (3.7 to 18.9 liters/hour)[a] for estimated average single-family residential cooler use.	- Relative humidity - Temperature - Number of hours of run time	Typical bleed-off water has high salts ranging from 375 to 4,043 mg/L, with average 1,580 mg/L.[b] Some evaporative coolers have a "sump dump" discharge, which often contains higher levels of total dissolved solids (TDS) than bleed-off.	Use bleed-off only on salt-tolerant vegetation. If TDS is < 5,000 mg/L, can irrigate salt-tolerant Bermuda and salt grass. If TDS < 2,000 mg/L can use on low-salt-tolerant plants such as citrus trees and almond, apple, peach, and pear trees.[b]
Air-Conditioner Condensate	Example discharge in dry conditions of Phoenix, Arizona:[c] 0.01 to 0.02 gal (0.04 to 0.07 liters) of condensate/hour for estimated average single-family air conditioner, 2-3 ton capacity. Condensate from a large commercial unit can reach 500 gallons (1,895 liters)/day.[c] Example discharge in humid conditions of Austin, Texas[d]: 0.1 to 0.2 gallons (0.3 to 0.7 liters) of condensate/hour for estimated average single-family air conditioner, 2-3 ton capacity. Condensate from a large commercial unit can add up to 2,000 gallons (7,580 liters)/day.[d]	- Relative humidity - Temperature - Ton-hours of run time: typical 2 – 3 ton capacity residential air conditioner may run 60% to 70% of the time on hottest, most humid days.[d] - Frequency of air exchange within building. Commercial buildings typically exchange air more frequently than similar sized residential units, so can produce more condensate. - Amount of humidity produced inside the building by various activities	AC condensate is typically high-quality water produced when humid air condenses on the cold evaporator or coil of an air conditioning unit.	Use salt-free condensate as irrigation source throughout landscape and garden in both humid and dry landscapes. Can use condensate to help leach accumulating salts from primary root zone in top 2 feet (0.6 m) of soil.
Reverse-Osmosis (RO) Water-Filter Discharge	Discharge of 2 to 5 gal (7.58 to 18.95 liters) per gallon of water purified. Assuming 1 gal/person/day (3.79 liters) drinking and cooking water needed, discharge would be 2 to 5 gal (7.58 to 18.95 liters)/person/day.		RO filter discharge water has about 25% higher concentration of TDS than the tapwater it is filtering.[e] It has no suspended solids.	Use as irrigation source on landscape and garden.

* gal = gallons

[a] Roy Otterbein, "Installing and Maintaining Evaporative Coolers," *Home Energy* magazine online, May/June 1996. http://www.homeenergy.org/archive/hem.dis.anl.gov.eehem/96/960511.htm

[b] Martin M. Karpiscak, Thomas M. Babcock, Glenn W. France, Jeffrey Zauderer, Susan B. Hopf, and Kennith E. Foster, "Evaporative Cooler Water Use in Phoenix," *Journal AWWA*,

Volume 90, Issue 4, April 1998

[c] Personal communication with Bill Hoffman, Austin Water Utility Commercial and Industrial Water Conservation Program Coordinator, 27 July, 2006

[d] Bill Hoffman, "Combining Storm and Rainwater Harvesting at Commercial Sites," First American Rainwater Harvesting Conference, August 21-23, 2003 Proceedings

[e] Ludwig, Art, *Create an Oasis with Greywater*, Oasis Design, 2006

Also assess their quality, availability, and accessibility when prioritizing and designing your harvests. You want to make sure the water's quality will be appropriate for your intended use, that you'll have enough water for your needs, that you'll have that water when you need it, and that you can get to that water—ideally being able to move/distribute the water to where you need it.

Greywater

Greywater is *available* when folks are sending water down the drain, so greywater "droughts" occur when you leave home on vacation.

Shower greywater in most households is the *highest quality*, *highest volume* greywater source (especially in the bathroom with the highest shower use) because it has a high water-to-soap/shampoo ratio. However, *accessibility* may be difficult without a stub-out (figs. 12.7A-11), crawl space beneath the floor, adjoining exterior wall (fig.12.32), or if the shower is lower than the landscape. An outdoor shower is often a more *accessible* option (12.25-12.28), though its *availability* may be limited to warm months if you don't like showering when it's cold out.

Laundry greywater can be one of the most *accessible* greywater sources since the washing machine is often located against (or can be moved next to) an exterior wall. However, laundry greywater tends to contain a higher soap-to-water ratio than shower greywater, so the *quality* of greywater discharged from washing machines varies more depending on the type and amount of soaps, detergents, and other chemicals used (see box 12.5).

Bathroom sinks are low-volume sources, and may be *lower quality* than showers due to the use of toothpaste and other toiletries, though there is often easy *exterior* access to drains, especially if they are located against an exterior wall.

Drinking fountain drain water quantity varies with use, and is typically of *high quality* since it lacks soap and solids.

Dark greywater

Reusing dishwasher dark greywater is especially challenging because of *poor quality* due in part to the high-salt content of detergents made for dishwashing machines, and so is typically not recommended.

Kitchen sink dark greywater is of *better quality* than dishwasher dark greywater if low- to no-salt dishwashing detergents are used to hand wash dishes (box 12.5). The *quantity* could be high if you cook a lot. Kitchen sinks typically have *easily* accessible drains located against exterior walls. Dark greywater from kitchen sinks and dishwashing machines requires special treatment due to the presence of food scraps, oils, and grease (see the Kitchen Resource Drains in Variations section).

Clearwater

Air conditioner condensate clearwater is an *easily accessible*, *high quality* source with *low volumes* produced in dry climates/seasons and *potentially high volumes* in humid climates/seasons (box 12.9). It's only *available* when the air conditioner, icemaker, or refrigerator is running.

Reverse osmosis (RO) water purifier drain water is *high quality*, available when the filter is used, and *easily accessible* if the filter is at a sink against an exterior wall (box 12.9). (Online, search "drain saddle" or "drain line adapter" for reverse osmosis filter to find parts that connect the RO filter drain to drain and greywater pipe).

Evaporative cooler bleed-off water is *available* when in operation and is *easily accessible*, but is *poor quality* due to its high salt content—though salt-tolerant vegetation can use this water if soil is occasionally flushed with salt-free rainwater (box 12.9).

Rainwater runoff

Rainwater runoff that is harvested in the soil is *available* when it rains. *Volume* is determined by rainfall and the size of catchment area it runs off of (boxes 1.3 and 1.4).

For rooftop runoff, *quantity* depends on rainfall and roof area. Roof runoff is typically of *high quality* since it contains little sediment, there are fewer life forms defecating on the roof compared to ground surfaces, and there are no cars leaking oil or people spraying herbicides on the roof. Quality also depends on the cleanliness of the air the rain passes through and the roof surfaces it flows over—steel, tile, and elastomeric paints that lack biocides tend to yield higher runoff quality. *Accessibility* to all points below the roof is typically great, unless downspouts are encased within the building and send flow directly to the sewer rather than to the landscape.

Street or parking lot runoff can be of *high volume* due to the typically large catchment area and high runoff coefficient (see calculations, appendix 2), but is of

low quality due to pollutants in the runoff. *Accessibility* is typically great unless catchment areas are lower than, or slope away from, the landscape.

Surface runoff from unpaved areas may or may not have pollutants such as human-made herbicides, oil, etc. It may be fertile due to organic matter and manures and may be high in sediment—the less ground-covering vegetation, the greater the runoff and the more potential for erosion and sediment.

Summary

So, depending on accessibility, high-quality, high-volume shower water is often the first greywater source I tap, followed by easily accessible washing machine water. When resources are limited, I tap the drains with the highest-use showers, avoiding the seldom-used ones such as those in a rarely used guest bathroom.

I prioritize greywater and dark greywater for my more water-needy perennial plants—especially fruit trees, but not annuals like vegetables. Exterior drinking fountains and condensate drains make great ephemeral "springs" for adjacent plantings. Roof runoff is great for all plantings, especially vegetable gardens. Street runoff is reserved for hardy perennial plants such as native woody perennial shrubs and trees, but not edible annuals such as vegetables that may uptake pollutants into their edible parts.

What's good for plants and soil is good for you

When you use your own greywater, you become very aware of the effects of products you put down the drain and wonderfully conscious of the fact that there is no "away." If you sent toxins down your greywater drain they would kill your plants, so you simply stop using toxic substances—which makes for a clear conscience and a healthier life and environment. Using greywater makes it obvious that we cannot throw any toxic materials "away" because they all stay on the planet with us. We may temporarily move toxins off site, but they invariably return via contamination of piped-in water, food purchased off site, the air we breathe, and the atmosphere that all life depends on. Thankfully the fewer toxic materials we use, the fewer will be discharged as waste on the planet.

Three-way valves for sinks, tubs, and showers (figs. 12.7B, 12.8 - 12.11), and multiple-drain options for washing machines (figs. 12.29 and 12.30), make greywater recycling practical for more people. This is because they don't have to immediately give up the occasional use of non-landscape-friendly soaps or cleansers containing boron, sodium, or chlorine. When such products are used, people can temporarily direct greywater to the sewer or septic system—though

the sewer/septic route does eventually deposit cleansers in a diluted form into fresh waterways, groundwater, lakes, or ocean bays.

Do not harvest greywater from a household using a water softener that uses sodium-based products such as sodium chloride, which is harmful to plants (though water softened with potassium chloride softeners is okay). And do not harvest the backwash from any water softener as it is extremely high in plant-harming salt.[17] Households using harvested rainwater as their primary water source do not need water softeners, since rain is naturally soft.

See box 12.5 for more on soaps and detergents.

GREYWATER HARVESTING STUB-OUTS

Greywater stub-outs are built-in plumbing connections that allow easy future access to a drain's water stream. Incorporating greywater-harvesting stub-outs at the time of construction, a room addition, or major renovation is generally the easiest and least expensive approach (fig. 12.7A, box 12.7), though retrofit installations are also doable. Ideally the upper end of a grey-water stub-out, along its diverter valve, is located for easy access to the greywater source—such as inside the bathroom beneath the sink, rather than inconveniently placed outside the house or under the floor. The low/downstream end of the stub-out pipe is routed to sections of yard that have ample space to place harvesting basins and greywater-supported vegetation. Stub-outs remain capped at both ends until a greywater distribution system is set up in the landscape. Then they can be connected to the drain plumbing and the greywater can be put to use.

Box 12.7. Requiring Greywater Stub-outs to Simplify Greywater Access and Use for Homeowners

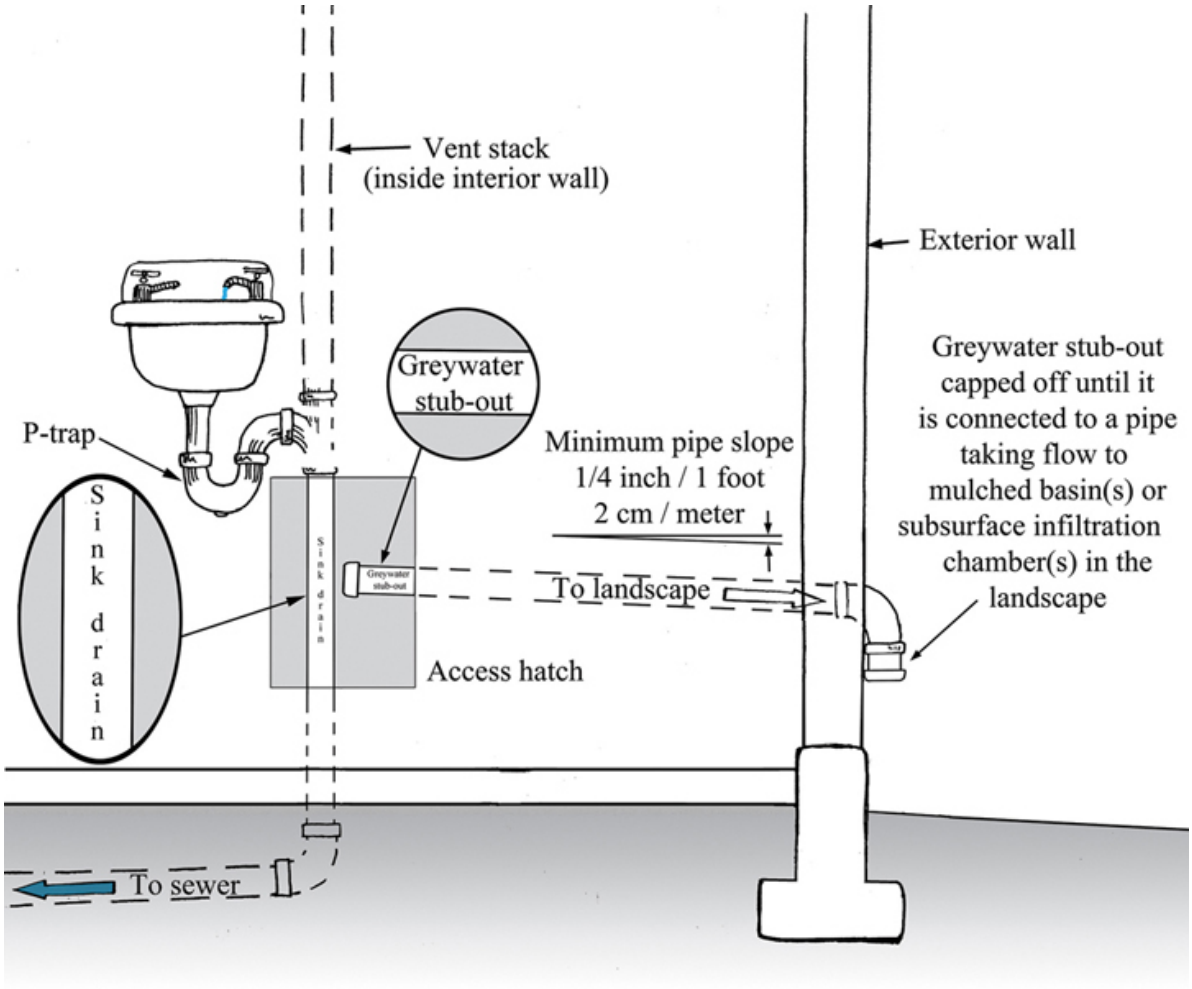
New homes in Tucson, Arizona, must be constructed with greywater stub-outs so homeowners do not have to cut through walls or jackhammer concrete floors to make greywater accessible for the landscape. Though not a perfect ordinance, it is improving with each revision to make it easier and less expensive for the homeowner to find and use the greywater plumbing. Search "Greywater-Harvesting Stub-Out Ordinance" at HarvestingRainwater.com for more.

Ideally stub-outs are connected using a three-way valve (figs. 12.7B, 12.8, 12.9 and 12.10) or a multidrain system (figs. 12.29 and 12.30). This enables the user to direct greywater to the landscape or to the sewer/septic system, depending on what goes down the drain, the weather, or soil saturation conditions. Greywater lines originating inside a home should be diverted downstream from P-traps and

vents to inhibit entry of insects, vermin, or odors into the house via greywater lines. The bottom of the P-trap is full of water preventing things like sewer gases from getting into the home via the pipe, and the vent creates an air break ensuring the water in the P-trap does not siphon out. Three-way diverter valves can often be installed as high in the system's flow as the vent/sewer stack, downstream of the P-trap (figs 12.7, 12.8). Search "Greywater Stub-Outs" and "Greywater Plumbing" at HarvestingRainwater.com for more information.

PATTERN: Humans are often like water: we take the path of least resistance. We do what is convenient.

PRINCIPLE: Whenever possible, make doing the right thing—such as irrigating with greywater rather than with drinking water—convenient, joyful, and conscious so you naturally do it. For example, place a greywater diverter valve, it's handle, or its optional electric switch, in an easy-to-reach, easy-to-see place in the same room as the greywater source (figs. 12.7 - 12.11). Clearly label the valve and where it directs the water, so you direct the water to where it is needed. Search "Diverter Valve Installations" at HarvestingRainwater.com for more examples.



12.7A. Greywater stub-out, not yet connected. The stub-out can be made accessible for later hookup by installing a removable section of drywall, a latched door, or by leaving it exposed within a below-sink cabinet. Note: Given the necessary 2% pipe slope inside the building, the stub-out should exit the building as high as possible for the maximum number of gravity-fed distribution options within the landscape.

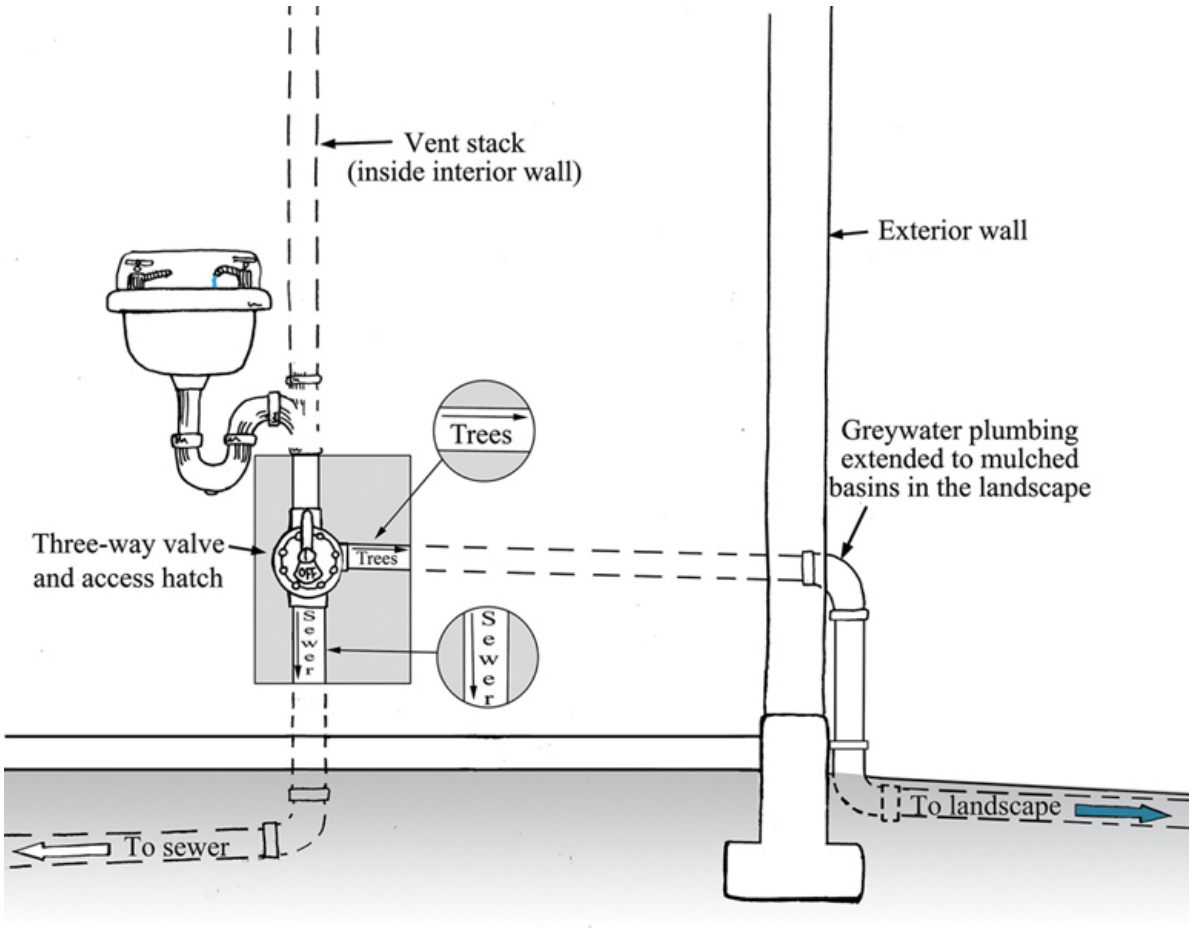


Fig. 12.7B. Greywater stub-out connected. The bathroom sink and drain are hooked up to the greywater stub-out via a three-way diverter valve. Before the sink is hooked up to the greywater line, the landscape end of this greywater line must be connected to an outlet point in the landscape. Option: once exiting the exterior wall, the pipe could be run horizontally at a minimum 2% slope along the wall before dropping into the soil to outlet the pipe higher in the soil profile. Search "Branched-Drain Plumbing" at HarvestingRainwater.com for an example

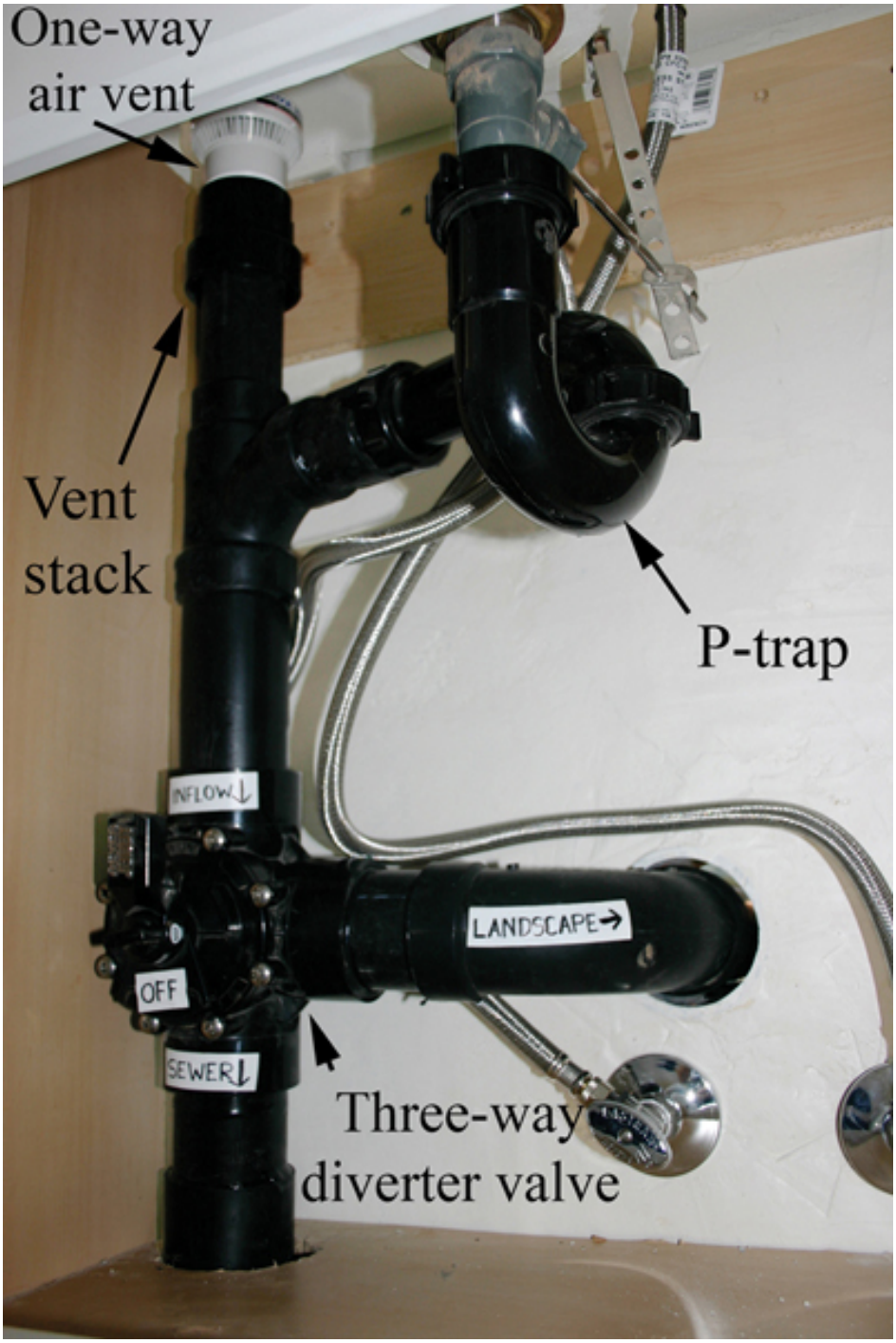


Fig. 12.8. Three-way diverter valve conveniently located in cabinet under a bathroom sink. Drain water goes down the sink drain, through the P-trap, down the vertical pipe/vent stack to the 3-way valve. The valve handle is cut shorter to fit the space. The vertical pipe/vent—with a one-way air vent [or air admittance vent] that sits atop the vent stack—creates an air break so water won't siphon out of the P-trap.

Fig. 12.9. Three-way diverter valve conveniently located between the toilet and sink directs sink greywater to the landscape or to the sewer at the Eco Hood in Phoenix, Arizona

Fig. 12.10. This bathtub was installed higher than normal to enable easy access to the tub's three-way diverter valve via a hidden door. Credit: Sonya Norman

Fig. 12.11. Electric switch for shower/bathtub grey-water's diverter valve, which has an *actuator* or electric motor that opens and closes the valve (not in photo). Design by Leslie Buerk, KalyxStudio.com.

For more examples search "Greywater Stub-Outs" and "Three-Way Diverter Valves" at HarvestingRainwater.com

Additionally, utilize greywater systems with the lowest maintenance needs, such as those featured in this chapter.

Existing homes can typically be retrofitted with simple techniques such as greywater stub-outs to sinks that are against exterior walls, cooler-bleed-off harvesting, the multi-drain system for washing machines, the "bucket and chuck it" system for apartments, and outdoor showers. These and other techniques are described in the Variations section of this chapter. See what works for you, your site, and your lifestyle. You don't have to do it all, just start somewhere. Anything is an improvement and the more you do the better!

MY PREFERRED GREYWATER SYSTEMS

There are many different ways to harvest greywater. Review your options to see what is most appropriate for the unique characteristics of your site, lifestyle, skills, and budget.

The seven greywater systems described in this chapter are relatively low maintenance and can be discharged into mulched infiltration basins. These systems are:

- **Branched-drain greywater system** (see next section) to simultaneously distribute greywater to multiple plants
- **Outdoor shower** that is quick, simple, inexpensive, great for summer, and a great alternative to indoor plumbing (see Variations section)
- **Multi-drain system for washing machines** that conveniently sends greywater to a different part of the landscape with each load of wash (see Variations and Real-Life Examples sections)
- **Bucket & Chuck It** is the least expensive— though perhaps the least convenient—system, since you collect greywater in a bucket and carry it where you need it. No permits is required because you don't change the plumbing (see Variations section).
- **Hand pump & siphon system** that allows inexpensive access to greywater from bathtubs or shower stalls whose drain pipes are inaccessible (see Variations section)
- **Kitchen Resource Drain** (KRD) that allows the legal reuse of kitchen sink water in Arizona (see Variations section)
- **Permitted household greywater and composting toilet combination** that enables home construction without a sewer or septic hook up (see Real-Life Examples section)

I prefer systems that disperse greywater via mulched and vegetated basins (figs. 12.12 – 12.14, box 12.10). Mulched basins do quadruple duty—they harvest rainwater and organic matter such as leaf drop, they both disperse and treat the greywater, and they grow plants. To make sure greywater pipes do not clog, greywater is discharged either a few inches above the mulch or into the void space of subsurface infiltration chambers (figs. 12.15 and 12.16). The systems described in this chapter do not incorporate drip irrigation or perforated pipes to disperse greywater because these systems typically add unnecessary complexity, costs, and maintenance. Drip-irrigation systems require pretreatment of the greywater to prevent clogging of emitters; perforated pipes tend to clog with roots.

Box 12.10. Advantages of the Greywater Systems Described in this Chapter

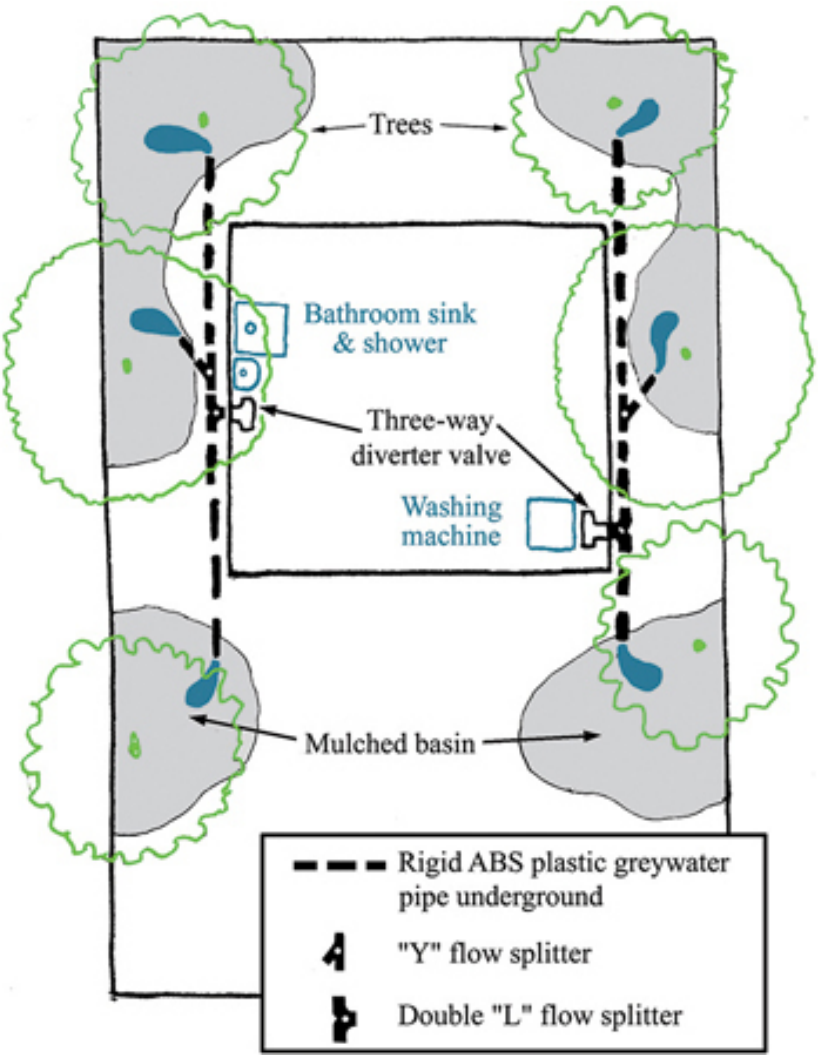
- *There are no storage tanks or pumps* to add complexity, maintenance issues, and costs. Gravity moves the water directly to the infiltration basin, which contains the surge of wat and quickly absorbs it in the soil. The hand pump and siphon system (Variations section) an exception. It relies on a siphon effect that is kick-started with a hand pump.
- *These greywater systems are ideal for creating a supplemental irrigation source*. Select greywater associated plantings from among low- to high-water-use non-riparian perennia species that can endure periods of time without greywater so they will be alive and well when you come home from vacation. Alternative wastewater-treatment systems that require continual applications of water—such as constructed wetlands with high-water-us riparian vegetation that is continually immersed in greywater or blackwater—cannot function unless you leave the water running while you are away.
- *There are no bad smells in these greywater systems* because there is no standing water. All water is quickly absorbed by mulch, soil, beneficial organisms within the soil, and vegetation, all of which act as natural filters. The Kitchen Resource Drain in the Variations section is an exception, since some water is "stored" in the grease trap. In this case, odor are vented through the household vent stack.
- *There are no manufactured filters* to complicate the system and require more maintenance
- *These systems are not prone to clogging with roots.* Unlike Infiltration trenches that have pipes, or septic leach pipes buried in gravel, these greywater systems discharge water wel above the mulch and soil, or within high-capacity subsurface outlet chambers. Roots wou have to grow through a large volume of air to get to the pipes. Outdoor shower drains ca be built with no pipes.
- *Greywater systems relieve strain on septic tank systems and municipal sewage treatment plants*. By reducing the volume of water discharged into septic tanks or municipal sewer treatment infrastructure, their lifespan and capacity are increased.

Note: This chapter provides enough information about greywater systems to understand conceptually what they can do and how to combine systems synergistically with rainwater harvesting. Real-world examples are included of

some of the greywater design innovations my friends, colleagues, and I use. These innovations are covered in detail because they cannot be found elsewhere. Other systems, such as the branched-drain system, which I also favor, are described in detail elsewhere and just summarized here. There are many additional systems that I do not discuss here. For complete information on greywatersystem design, construction details, use, and maintenance, see Art Ludwig's *The New Create an Oasis with Greywater.* For information on dealing with permits, larger systems, or making greywater systems for others, see his *Builder's Greywater Guide*. Much of the material in this chapter is drawn from or inspired by these books. More information can be found in appendix 4, Resources.

BRANCHED-DRAIN GREYWATER SYSTEM

To meet most needs, my favorite system is Art Ludwig's branched-drain greywater system (figs. 12.12-13, 12.23). It is very easy and convenient to use, requires little maintenance, and can be incorporated into many greywater systems. However, it takes a little more work and care to properly design and install, so you'll need Art's detailed instructions in his book *The New Create An Oasis with Greywater*. The introduction provided here enables you to conceptualize how to integrate the branched-drain system with your rainwater-harvesting earthworks.


Trees
Bathroom sink & shower
Three-way diverter valve
Washing machine
Mulched basin
Rigid ABS plastic greywater pipe underground
"Y" flow splitter
Double "L" flow splitter

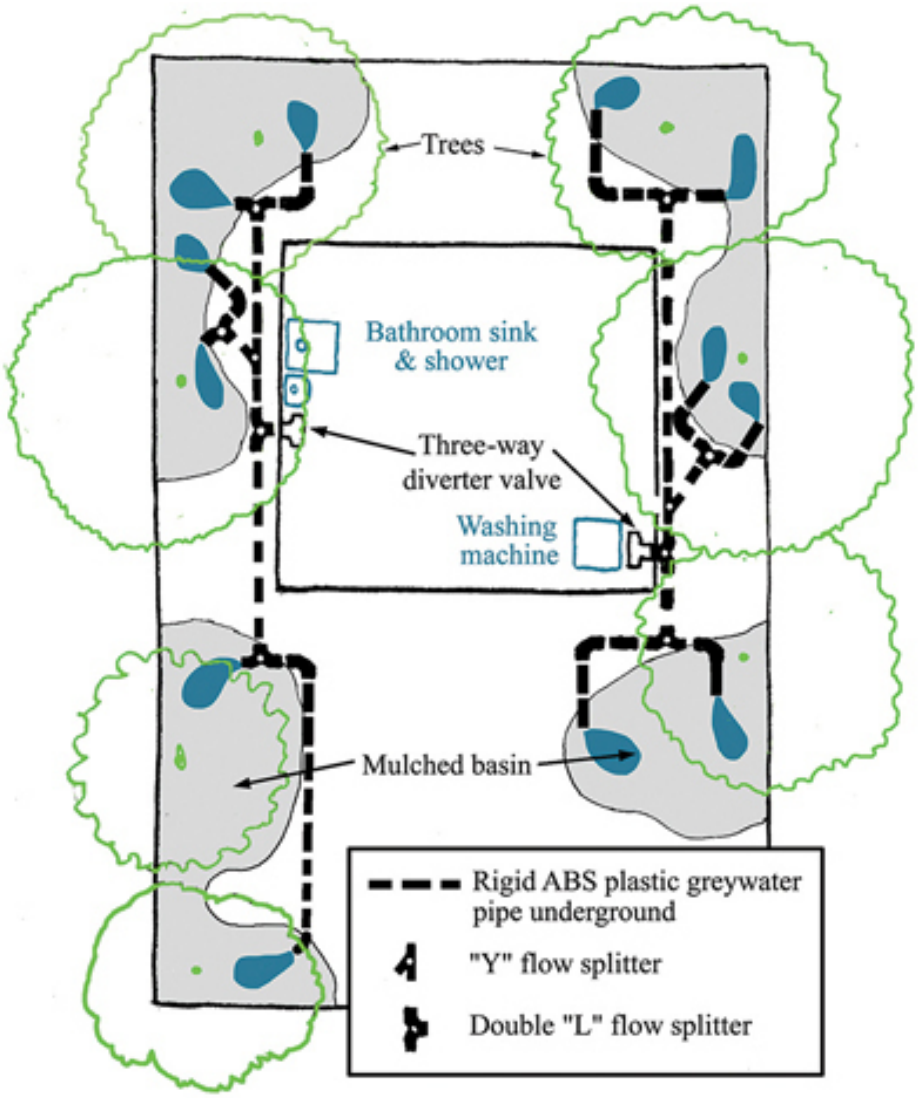


Fig. 12.12. Two branched-drain greywater systems. One for a low-water-use household (top). One for a higher-water-use household (bottom). Flow splitters and underground pipes direct greywater to a total of six outlets within mulched basins on the left, and 12 outlets on the right. Note: greywater pipe is located under raised paths to allow easy access and to keep the pipe higher in the soil profile.

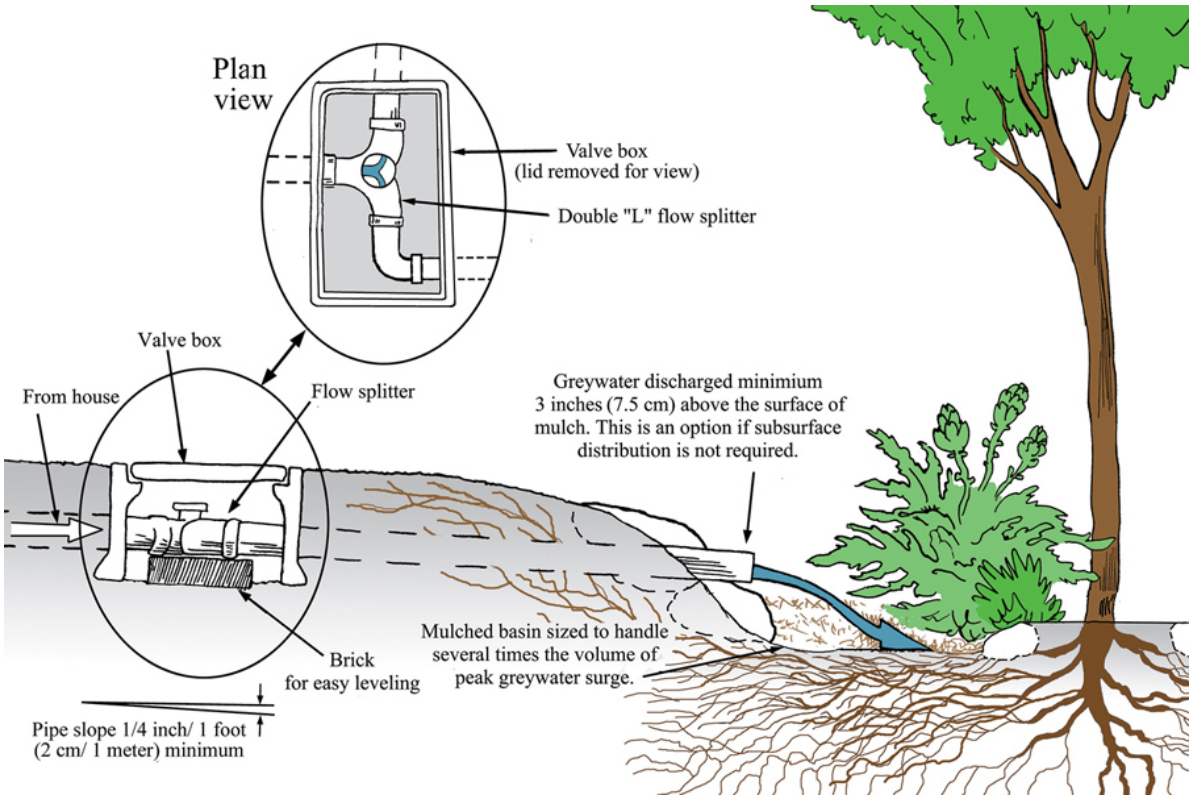


Fig. 12.13. Discharge of greywater into a mulched and level-bottomed basin for even infiltration of water throughout the basin (elevation view). Maintaining a clear space between the end of the pipe and mulch is key to keeping solids from backing up in the pipe and keeping roots from growing into and clogging the pipe. Note placement of flow splitter in valve box for easy access. Adapted from the *The New Create an Oasis with Greywater*

Branched drains use gravity to passively distribute greywater from household drains via 1.5- to 2-inch (40- to 50-mm) diameter pipe that maintains a minimum 2% slope (1/4-inch drop per linear foot [2-cm drop per meter]). Flow can be split or branched multiple times to create as many as 16 outlets to distribute greywater among landscape basins. However, low-volume systems should have ten or less outlets. "Double L" or "Y" fittings are used as the flow splitters. Search "Greywater Plumbing" at HarvestingRainwater.com for information on how to make your own flow splitters and to see an image gallery of branched drain plumbing.

This system conveniently spreads greywater around, reducing the chance that any one area becomes over-watered. Wide distribution is further enhanced when greywater lines from different sources are directed to different areas of the landscape to deliver greywater over a larger area. For example, keep greywater

lines from different sources, such as laundry and bathroom, separate and send them to different areas (fig. 12.12). You can combine greywater lines from different sources, but more pipe will be needed to redisperse and distribute the combined greywater flow to a large area.

Discharge of greywater into mulched basins

Discharge of greywater into mulched basins is the simplest system to design and install, and is legal in Arizona, New Mexico, West Texas, California, and a growing number of other states. Greywater infiltrates into the soil beneath the surface of the mulch, never overflows out of correctly-sized basins, and does not puddle on the surface of the soil. The basins should be sized to contain and infiltrate the peak surge of greywater that will be discharged in a short period of time (see Conceptualizing and Planning section for how to do this). This enables greywater to adequately infiltrate into the soil, while preventing oversaturation even when the soil is already moist from rainfall or previous greywater discharges. Plant trees and other perennial vegetation in association with these basins to increase the rate of infiltration and utilize the greywater and rainwater they collect (fig. 12.14).

12.14. Placement of plants in relationship to greywater outlets in a mulched basin. The beige pipe in the lower right of the photo delivers water from a washing machine. The black pipe (slightly above the beige pipe in the photo) delivers greywater from an outdoor bathtub/shower, In less than ten minutes, all the greywater infiltrates into the living soil and roots. Plants utilize this greywater all year long. The tree planted to the left is the primary perennial plant in the mulched basin. Smaller annuals and perennials are planted closer to the greywater outlets where their smaller root systems can utilize the water. The edible parts of all these plants are either cooked before eating or are high enough above the ground so harvested parts do not come in direct contact with greywater. This safe and effective system has served me well for over 20 years. Note: ideally the two greywater pipes would be further apart to spread the water through more of the basin, but constraints at this site prevented that. Under the corks are buried unglazed ceramic irrigation ollas. These are periodically filled with rainwater via a hose from the cistern. (See Planting Water in Pots in the Real-Life Examples section of chapter 2 for more).

Discharge of greywater into subsurface outlet chambers

The branched-drain greywater system gets slightly more complex if you add installation of *subsurface outlet chambers*—also called leaching chambers or

infiltration chambers—to the ends of greywater drain pipes. These empty, bottomless, plastic chambers help ensure that greywater always remains beneath the surface of the chamber, soil, and mulch, enabling you to get your system permitted in areas with more restrictive requirements for subsurface drainage (figs. 12.15A, B, C, 12.16).

Fig. 12.15A. A two-Infiltrator system using Quick4 Plus Standard Chambers that are linked together and sized (in total) to handle the peak surge of dark grey-water entering the system. A flow splitter in the valve box divides the flow, directing half into each end of the elongated chamber run. This increases the total area of soil regularly watered, while reducing the chance of the soil going anaerobic—which could occur if all the water was directed to one end of the chamber. Use non-rusting stainless steel brackets and screws to hold all components in place at the desired slope. Due to the strength of corrugations in the chambers, they will not collapse if you walk or stand on them. Tucson, Arizona

Fig. 12.15B. The chambers and pipe are now covered with soil and mulch and planted over. The chambers receive dark greywater from the kitchen sink, "wastewater" from a reverse osmosis water filter, and (nine years after installation) urine from the urine diversion of a compost toilet. All elements have worked great for the entire ten years of its use. Following the establishment period, all native plants have been irrigated solely by harvested

greywater and direct rainfall. The pomegranate gets supplemental irrigation in dry months and when residents are out of town to reduce splitting of fruit.

Fig. 12.15C. Abundant beneficial life in the form of earthworms is pulled from the bottom of the chambers via the inspection pipe. Note: The inspection pipe can be cut shorter and hidden with its lid under a rock if desired.

Fig. 12.16. The healthy interior of a three-Infiltrator system's infiltration chambers linked together and appropriately sized for the site's peak surge of greywater and the soil's percolation rate. Earthworms cover much of the soil. Lama, New Mexico

Subsurface outlet chambers are also useful for very small yards that lack space for a basin, since you can walk over the soil-covered chambers. They are also useful when the depth of a greywater drain pipe makes draining water into a mulched basin impractical. This can occur on flat sites where greywater may exit the home at a lower than ideal elevation, then must drop further to maintain the minimum 2% pipe drop out to the landscape.

Subsurface outlet chambers work particularly well for dark greywater from a kitchen sink, which has a higher bacteria count than regular greywater. This dark greywater might attract dogs and other critters to the scent of your rinsed-off dinner if this water was outletted above the surface. Infiltration chambers also work great for septic leach fields since you can plant fruit trees beside them to utilize this fertile "wastewater."

Outlet chambers can be covered in soil only if they are correctly sized to handle the entire peak surge of greywater. To properly size your chambers for that peak

surge, see the next section on Conceptualizing and Planning. There are several ways to reduce the needed chamber size:

- Reduce the peak flow of greywater into any one chamber by:
  - Branching or splitting the greywater flow so it goes to multiple chambers or basins to reduce the flow to any one point
  - Reducing the overall flow into the system by replacing, for example, an old high-water-use washing machine with a newer low-water-use machine or replacing a high-flow shower head with a low-flow shower head
  - Diverting part of peak flows to the sewer with either a three-way valve or a multi-drain system

- Place chambers within large mulched infiltration basins, then cover the chambers with mulch rather than soil so each basin becomes an extension of the chamber(s) within it. Greywater can then quickly overflow from chambers to the larger capacity basins, while remaining beneath the surface of the mulch. It is key that the bottom of the basin be uniformly level— including under the chamber— otherwise an anaerobic pond may form in the low spot beneath the chamber.

Subsurface outlet chambers can be bought from manufacturers—often suppliers of septic systems—or can be made from reused materials. Large, bottomless premanufactured outlet/leaching chambers—with louvered sides that enhance water infiltration—are inexpensive, durable, and come ready to install. They are unlikely to clog with roots due to their large void spaces, which are a great deal larger than the perforated pipe typically used in French drains and septic leach fields. See Hancor.com or InfiltratorSystems.com for outlet-chamber suppliers. See product examples in figs. 12.15A, B, C, 12.16). In order to discharge greywater high in the soil profile where more roots and soil life can utilize and filter the water, do not use chambers taller than 13 inches (33 cm). Low-profile chambers (8 inches or 20 cm high) are available from InfiltratorSystems.com.

You need to maintain access to chambers to be able to dig them up for inspection and maintenance (figs. 12.17, 12.18), so don't plant perennial plants over chambers. You can plant perennials several feet (60 cm) or more from the sides of the chambers.

Fig. 12.17) This greywater system in Corvallis, Oregon, "failed" 6 years after installation due to a build up of earthworm castings, and roots growing in those castings. Photo was taken just after most of the chamber was removed for inspection. To fix it, the castings were harvested and the roots were cut back. It was then reassembled with the addition of two layers of 6-mil plastic sheeting put over the chamber to prevent root entry through the side louvers. The system has worked great in the 10 years since. Credit: David Omick

Fig. 12.18. A failed single-chamber system that did not have sufficient capacity for the soil's percolation rate and the site's peak flow of laundry greywater. This peak flow occurred when the family returned from vacation and did all their laundry in a single day. As a result, the soil within the chamber became anaerobic—the telltale sign being the resulting black slime covering the soil. In addition, the infiltration rate of the now anaerobic soil was dramatically reduced resulting in the shower drain taking a very long time to drain. To fix it, the needed chamber capacity was calculated for the peak greywater volume. In this case three chambers were required rather than one. Two additional chambers were installed after scraping the anaerobic slime out of the original chamber. Soil has since stayed aerobic and the system has worked well. Credit: Lincoln Perino

For more images search "Infiltration Chambers" at HarvestingRainwater.com.

PATTERN: Aerobic soil—unsaturated soil that contains air/oxygen—smells good. Aerobic soil has open pore spaces into which water can infiltrate, so water does not pool on the surface.

Anaerobic soil—saturated soil that does not contain air/oxygen—often smells bad. Since it is waterlogged, no additional water can infiltrate into

anaerobic soil so water pools on its surface (fig. 12.18).

PRINCIPLE: Rapidly infiltrate greywater into the soil to keep your system smelling good and avoid exposed greywater. Soil life can then filter and utilize the greywater, and greywater won't pool on the surface, keeping people and animals from coming into direct contact with the exposed greywater. To rapidly infiltrate greywater, design aerobic systems following all six steps in the Conceptualizing and Planning section below.

DEVELOPING A GRAVITY-FED GREYWATER SYSTEM

CONCEPTUALIZING AND PLANNING

To develop a greywater system, start by gathering site information. Sketch potential locations of grey-water sources, piping, and basins to support existing and planned vegetation. You can do this on a print out of an aerial photo of your site from GoogleMaps or GoogleEarth. Follow the water-harvesting principle of *maximizing beneficial relationships and efficiency by "stacking functions"* to design a flourishing oasis zone close to your home that will shade and cool in summer, and let in sun and warmth in winter. See Volume 1, chapter 4 (and figs. 1.8, 1.9, and 11.7 in this book) to see how to maximize both summer shade and winter sun.

Follow the six steps below to develop a greywater plan. Record the data you gather on your plan (see figs. 12.20, 12.22).

STEP 1. Find and mark all existing underground utilities, so you don't accidentally damage them when you dig.

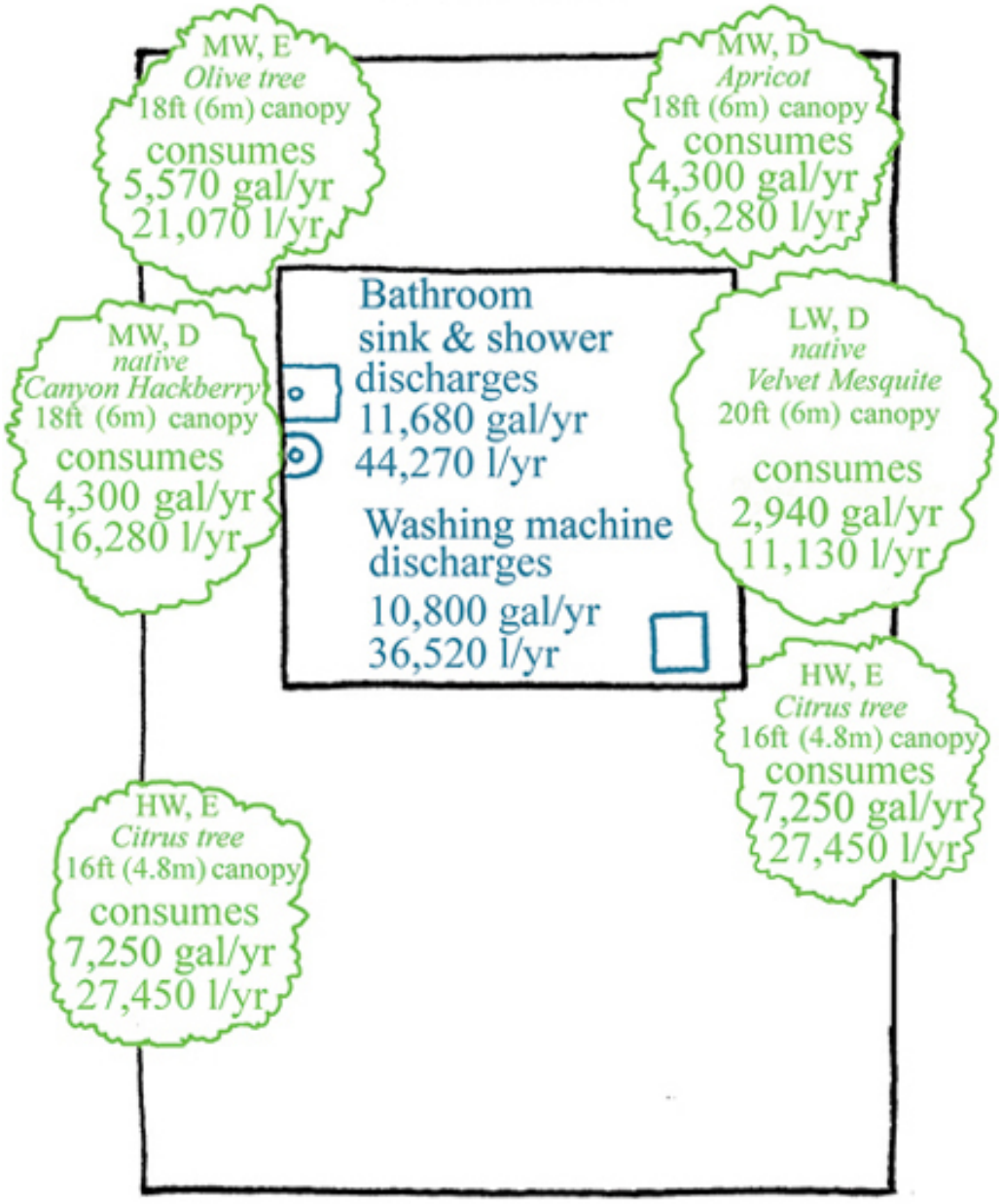
In the U.S. call 811 for a free service that will find and mark all the site's underground utilities from the main to the meter such as gas, water, sewer, and electric. If the meter is not on or beside your house, you may also need to refer to your building plans to determine where the lines are between the meter and your home. Your municipality or county should have copies of the plans if you don't.

STEP 2. Determine what greywater sources are accessible, where in the yard you can easily distribute that greywater (with gravity, and where you need to irrigate existing or planned vegetation (figs. 12.19 and 12.20).

Fig. 12.19. Horizontal distance from the greywater stub-out pipe to the desired basin and fig tree location is measured at 7-foot (2.1-m). To maintain a minimum 2% slope (drop 1/4 inch per foot, or 2 cm per meter), the pipe to the basin needs to drop about 2 inches (5 cm). The land surface elevation where the basin will be dug is currently 4 inches (10 cm) higher than the bottom of the greywater stub-out pipe (measured using a water level). See appendix 1 for how to make and use a water level.

To determine how deep to dig the basin, take into account the 2 inches (5 cm) of needed pipe drop and the 4 inches (10 cm) of higher land that needs to be removed. Add room for 4 inches (10 cm) of organic mulch, and add room for a 2 to 3-inch (5- to 8-cm) gap between the bottom of the greywater pipe entering the basin and the top of the mulch. So, the basin will need to be dug down at least 13 inches (2 + 4 + 4 + 3 = 13) or 33 cm (5 + 10 + 10 + 8 = 33). Note: The sidewalk will be replaced or covered with a raised earthen path that slopes/drains away from the house. Note: if needed, sometimes stub-out locations can be raised.

Water-conserving household



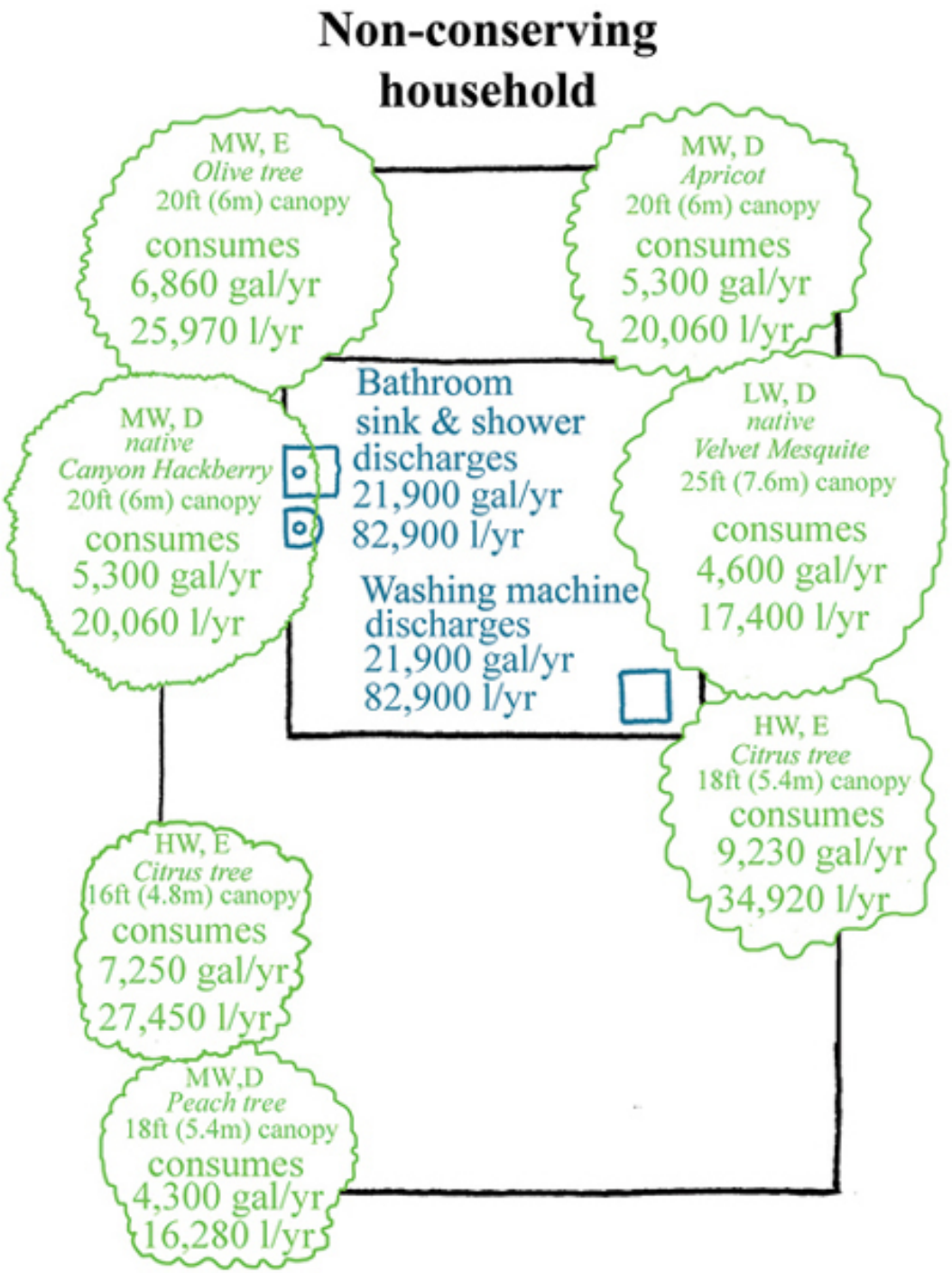


Fig. 12.20. Sample site plans show average annual grey-water discharge for a water-conserving household (top) and non-conserving household (bottom) where four people live (based on boxes 12.6 and 12.8, then rounded to even numbers). In addition, annual water needs of trees within easy reach and downslope of household greywater sources are shown. Water needs are based on appendix 4, in Volume 1. (LW = Low-water-use tree, MW = medium-water-

use tree, HW = high-water-use tree, D = deciduous, E = evergreen, native = native plant)

Consider potential outdoor shower locations if shower drains are currently inaccessible because they are encased in a concrete floor in the middle of the house. Or consider moving your washing machine from the interior of the house to a spot against an exterior wall if needed.

STEP 3. Estimate the volume of your accessible average greywater discharge (see fig. 12.20 and boxes 12.6 and 12.8) to determine the volume of greywater available for irrigation. Then estimate the irrigation needs of your existing or planned landscape.

Using the figures from box 12.8 (and calculations below) we created an example of average annual grey-water discharge for a water-conserving household of four people on the left-hand side of fig. 12.20:

- Shower: 4 people × 1 shower/person/day × 6 gallons (22.7 liters)/shower = 24 gallons (90.8 liters) average daily discharge
- Bathroom sink: 4 people × 2 gallons (7.6 liters)/ person/ day = 8 gallons (30.4 liters) average daily discharge
- Shower and sink: 24 gallons (90.8 liters) daily shower discharge + 8 gallons (30.4 liters) daily sink discharge = 32 gallons (121.2 liters) average daily bathroom greywater discharge

For average monthly figures, multiply the daily figure by 30 days.

For average annual figures, use estimates of use/person/year from box 12.8 for the calculations above, rather than using estimates of daily use per person.

To estimate irrigation needs for specific plants, see appendix 4 in Volume 1.

To get a ballpark estimate of your current outdoor monthly water use, compare your water bills from the irrigation season—typically drier summer months, to a season when little or no irrigation is needed—typically winter months. The difference is more or less your outdoor water use.

Average greywater discharge can meet 71% (22,480 gallons [85,096 liters]) of the irrigation needs in the water-conserving household (fig. 12.20). Ideally, harvested rainwater makes up the remaining 29% (9,130 gallons [34,560 liters]) of the landscape's water needs. Native trees can get this from passive earthworks, but less hardy exotic fruit trees will likely also need cistern water to make up the difference in dry seasons. At sites with lower available water, reduce plant density and size, or switch to lower-water-use plants.

In the non-conserving household (fig. 12.20), the higher volume of greywater discharge can allow for an increase in plant density and water use, and/or plant size. Greywater discharge can meet 100% (42,840 gallons [162,167 liters]) of current irrigation demand. As the household begins to conserve water, available greywater will decrease and the need for rainwater harvesting will increase. At this site, higher greywater discharges will require larger basins or subsurface chambers (step 4).

STEP 4. Size basins or subsurface chambers based on the expected peak greywater flow in a day and on your soil's percolation rate to avoid the unwanted scenario in fig. 12.18.

Estimating peak greywater flow in a day

What is the possible peak (extreme) greywater flow in a day for your household?

Let's say you want to harvest shower greywater in your one-bathroom, water-conserving household, which has a low-flow 1.8 gallon/min (6.8 liter/minute) showerhead. You usually have 4 people showering 5 minutes each once a day. But how much greywater would be produced if you had 2 guests and everyone (6 people) showered twice in one day (maybe you all played in mud puddles after your morning showers).

Using water use estimates in box 12.8:

6 people × 2 showers each × 9 gallons (34 liters)
per shower = 108 gallons (408 liters) peak daily flow rate. Remember that number.

Estimating the percolation/infiltration rate of your soil

Do a simple soil percolation/infiltration test in the area(s) where you plan to harvest greywater (box 12.11).

After estimating peak daily flow and then doing an infiltration test for the soil where you plan to infiltrate your greywater, use table 12.1 to determine the minimum infiltration surface area you need on the bottom of your mulched basin(s) or subsurface chamber(s) based on the estimated peak daily flow they will receive.

Box 12.11. How to Do a Simple Percolation/Infiltration Test of Your Soil

Note: I prefer the term "infiltration", but I also use the term "percolation" here as that is the term often used by regulators when they require a "perc" or "percolation test" to see

how quickly water percolates into your site's soil.

TO TEST:

1. Mark all locations where you intend to locate a greywater-harvesting mulched infiltration basin and/or outlet chamber for greywater or kitchen sink drain water. At each location where you plan to infiltrate greywater or kitchen sink drain water, dig a circular hole about 15 inches (38 cm) in diameter and about 12 inches (30 cm) deep. The sides of the hole should be vertical and the bottom should be level.

2. Slowly fill the hole with water.

3. As the water level in the hole drops, refill the hole with more water. Continue to do this at least three times over several hours. This will saturate the soil around the hole to simulate a worst-case scenario of very rainy conditions and peak greywater flow.

4. Once the soil is fully saturated, fill the hole with another 6 inches (15 cm) of water. Now you are going to take some measurements. Either place a metal ruler vertically into the hole, securing it in place (fig. 12.21); or thrust a stick into the side of the hole to mark the starting water level, and use a tape measure to measure the change in water level on the stick.

5. Note the number of minutes it takes for the water level to drop (infiltrate) 1 inch (1 cm). This is a first estimate of your soil's infiltration rate in minutes per inch (or minutes per cm).

6. Repeat steps (4) and (5) the next morning after clay particles in the soil have had time to swell up. If there is a difference in the infiltration time from the previous day, use the longer time as your soil's infiltration rate.

Based on that infiltration rate, see Table 12.1 to size your greywater-harvesting basins or to determine the number of subsurface outlet chambers needed.

(If you are getting a permit for a new home in Arizona with a greywater-harvesting system and composting toilet, but no sewer or septic system, see box A3.2 in appendix 3 as well. Use this information to refine the number of required chambers for your permit for a Kitchen Resource Drain (KRD), described in this chapter's Variations section).

7. As Art Ludwig says, *"If water takes hours to drop an inch, if water infiltrates an inch in less than a minute, or if the hole fills with water by itself, you've got a problem!"*[18] If any of these scenarios occur, find another location for your mulched basins or subsurface outlet chambers or consider a different system (see appendix 4 as well as Art Ludwig's website, OasisDesign.net, for resources on other greywater systems).

Fig. 12.21. Conducting a soil infiltration test, measuring the infiltration rate using a watch and ruler.

Table 12.1. Maximum greywater loading rates and minimum greywater infiltration areas based on soil's infiltration rate and peak greywater discharge volumes.

Row	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
	Soil's infiltration rate, *minutes/inch*	Maximum loading rate of infiltration area, *gpd/ft²*	Infiltration surface area needed for peak greywater volume, *ft²/gpd*	Soil's infiltration rate, *minutes/cm*	Maximum loading rate of infiltration area, *liters/m²/day*	Infiltration surface area needed for peak greywater volume, *m²/liters/day*
1	0-30	2.5	0.4	0-12	102	0.010
2	30-45	1.5	0.7	12-18	61	0.017
3	45-60	1.0	1.0	18-24	41	0.025
4	60-120	0.5	2.0	24-47	20	0.049
	ft²/gpd = square feet of infiltration area needed per gallon per day			cm = centimeter m² = square meters		
	Note: These rates are conservative. Can be up to 3-5 gpd/ft² (122-204 liters/day/m²) for greywater, up to 10 gpd/ft² (407 liters/day/m²) for secondary treated effluent. Note: Adapted from *The New Create an Oasis with Greywater* by Art Ludwig					

Box 12.12. How to Use Column 2 (or Column 5 in Metric) in Table 12.1

Use column 2 (column 5 in metric) to figure out how much greywater you can send to an infiltration area in a day without the soil going anaerobic (water-logged, lacking oxygen, and stinky). This is called the maximum loading rate.

For example, let's say you have 15 square feet (1.39 square meters) of unpaved area in a tiny yard, where it takes 35 minutes to infiltrate an inch of water (14 minutes to infiltrate a centimeter). Column 1, row 2 contains your 35 minutes/inch infiltration rate. Go to column 2 (column 5 for metric) to help calculate the maximum loading rate—the maximum volume of greywater you can send to that area—given your infiltration rate, doing the following calculation:

15 square feet of infiltration area × 1.5 gallons maximum loading rate per square foot per day = 22.5 gallons per day maximum loading rate for that 15 square foot infiltration area.

Or in metric 1.39 square meters of infiltration area × 61 liters maximum loading rate per square meter per day = 85 liters per day maximum loading rate for that 1.39 square meter infiltration area.

For example, let's say your soil's infiltration rate is 35 minutes, which means it takes 35 minutes for an inch of water to infiltrate into the saturated soil (14 minutes to infiltrate a centimeter into saturated soil). Go to column 1 on table 12.1 (column 4 for metric units). Find the line below that contains your soil's infiltration rate, which in this case is row 2. Remember, in Step 4 earlier, you calculated your peak daily flow rate as 108 gallons (408 liters). Now move to the

right along row 2 to column 3, where you see that the infiltration surface area needed is 0.7 square feet per gallon per day. Now do the following calculation:

108 gallons peak greywater flow per day × 0.7 square foot of infiltration area per gallon per day = 75.6 square feet minimum infiltration surface area at the bottom of basin or subsurface chamber to infiltrate your peak flow of greywater.

Or (in metric): 408 liters peak greywater flow per day × 0.017 square meters of infiltration area per liter per day = 6.9 square meters minimum infiltration surface area at the bottom of basin or subsurface chamber to infiltrate your peak flow of greywater.

That's a big basin! Or if you're using subsurface chambers, you'd need seven of them (each Quick 4 Plus Low Profile chamber having 11.32 square feet or 1.05 square meters of bottom surface area within them). The needed basin/chamber size would increase even more if you had a slower soil infiltration rate.

The easiest way to reduce the basin size or number of chambers is to reduce the volume of greywater entering the system.

Just switching from a 1.8 gallon/minute (6.8-liter/minute) showerhead to a 1 gallon/minute (3.8-liter/minute) showerhead would reduce the peak daily flow to 60 gallons (227 liters) and the needed basin or chamber bottom surface area to 42 square feet (3.9 m^2), requiring four chambers.

Another option to reduce the peak flow is to divert some greywater flow to the sewer or septic system (figs. 12.7B – 12.11), but you might not remember to divert it, so don't count on that when sizing your system.

You can increase the infiltration rate of water into soil over time by increasing roots, organic matter, and life in the soil. Do this by planting within and beside the basin or near the chamber(s) to increase roots. Add compost and/or wood chip mulch to support beneficial soil microorganisms such as mycorrhizal fungi.

You can reduce the size of a single basin or single chamber run by diverting the greywater flow to additional basins or chamber runs. Size the combined surface area of all the basins or chambers to handle the peak daily flow (see step 5).

STEP 5. Determine your options for diverting grey-water flow to multiple destinations.

See fig. 12.22. Options include the branched drain described earlier; the multi-drain for washing machines, the "bucket and chuck it," and/or the hand pump and siphon systems described later in the Variations section; and still other

systems found in Art Ludwig's book *The New Create an Oasis with Greywater* and others in appendix 4.

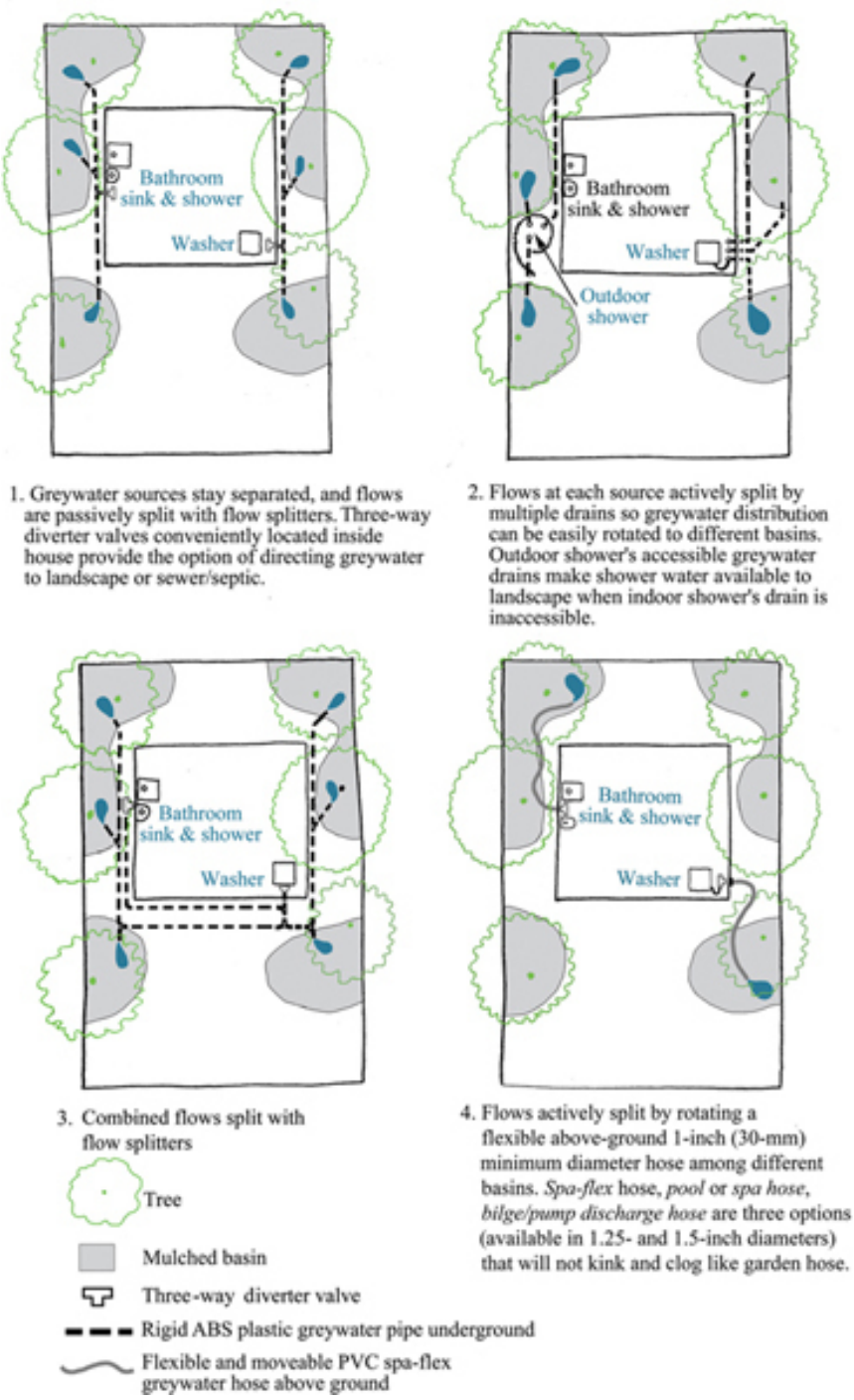

Bathroom sink & shower
Washer
1. Greywater sources stay separated, and flows are passively split with flow splitters. Three-way diverter valves conveniently located inside house provide the option of directing greywater to landscape or sewer/septic.
Bathroom sink & shower
Washer
Outdoor shower
2. Flows at each source actively split by multiple drains so greywater distribution can be easily rotated to different basins. Outdoor shower's accessible greywater drains make shower water available to landscape when indoor shower's drain is inaccessible.
Bathroom sink & shower
Washer
3. Combined flows split with flow splitters
Bathroom sink & shower
Washer
4. Flows actively split by rotating a flexible above-ground 1-inch (30-mm) minimum diameter hose among different basins. *Spa-flex* hose, *pool* or *spa hose*, *bilge/pump discharge hose* are three options (available in 1.25- and 1.5-inch diameters) that will not kink and clog like garden hose.
Tree
Mulched basin
Three-way diverter valve
Rigid ABS plastic greywater pipe underground
Flexible and moveable PVC spa-flex greywater hose above ground

Fig. 12.22. Four different options for diverting and distributing greywater flow around a yard. The bottom right example is the least convenient as you need to periodically move the flexible hose to another basin. Adapted from *The New Create an Oasis with Greywater*

STEP 6. Draw a plan of your chosen greywater distribution system(s) from source to outlets.

See figs. 12.12 and 12.22. You can draw on an aerial image from Google Earth or Google Maps. Also mark your site's underground utilities on this plan, and do not place trees below overhead utilities like electric lines to avoid conflicts.

DESIGN AND INSTALLATION

With Art Ludwig's *New Create An Oasis With Greywater* and this guide, you can do the outside work yourself, and effectively monitor the work of a plumber inside the house. Plumbers are experts on the vents, P-traps, and interior (or "collection") plumbing that links fixtures in the house to one or more outside distribution points. But the utility of plumbers often ends when greywater pipes exit the house and enter the yard. Many plumbers do not realize the need to discharge greywater in the top two feet (0.6 m) of soil where most roots grow and soil life flourishes. They often place the greywater line too deep—sometimes in the same trench and at the same depth as the sewer line. Plumbers may also prioritize a strategy that is quickest and easiest for them, rather than what will be ideal for you. So be clear with the plumber about what you need for your greywater system.

Keep the points where greywater lines connect to drain pipe in the home as high as possible to give you the maximum potential distance for gravity-fed distribution of greywater throughout the yard, while maintaining a minimum pipe slope of 1/4 inch per foot (2 cm per meter). If you don't connect to water sources as high as possible, given the minimum pipe slope needed, the end of the outlet pipe could be too deep for effective irrigation of plants that are far from your greywater source or in yards that slope up a bit. To determine the slope of your site and pipe see figs. 12.19 and 12.24, and see appendix 1 for simple, inexpensive tools to determine pipe slope and how to use them.

Fig. 12.23. Branched drain system under construction. Pipe is run within raised pathways, so it will always be easy to find and access. This also keeps the pipe run higher, so you can have longer runs if necessary and still outlet the pipe in basins well above where the mulch will be applied. Flow splitters are positioned in valve boxes. Search "Branched-Drain Greywater Distribution Plumbing" at HarvestingRainwater.com for many more illustrated design and installation tips.

Fig. 12.24. Measuring a 2% slope on greywater pipe. See Tool Box Level in appendix 1 for more.

MAINTENANCE

The systems described in this book are specifically designed for low maintenance. However, remember the water-harvesting principles of *long and thoughtful observation* and *continual assessment of your system: the feedback loop*. Always pay attention to the health of plants being irrigated by greywater and other onsite waters. Are they getting too much water (soil is perpetually wet) or too little (leaves are less vibrant, maybe starting to curl or yellow). Are any of the soaps, cleansers, or other things you are sending down the drain stressing your plants? Make any needed changes. In dryland areas with less than 20 inches (508 mm) of annual rainfall, periodically apply harvested rainwater (or fresh water if harvested rainwater isn't available) to all plantings to leach out accumulated salts from soaps and detergents.

Soils should drain quickly enough so there is no standing water around plants that could lead to harmful anaerobic conditions. The root crown at the base of

most plants should be above the expected level of incoming rainwater and greywater to reduce the chance of rot.

See the book *The New Create an Oasis with Greywater* for more maintenance tips.

VARIATIONS

OUTDOOR SHOWER

Outdoor showers can provide easily accessible greywater right where it is needed. At a minimum, sling a hose with a spray nozzle over a branch that overhangs a mulched basin, and you've got a low-cost, easy-to-install outdoor hose shower. It's refreshing to use in the summer when plant water needs and your shower needs are the greatest. Many modern garden nozzles have a convenient shut off valve along with as many spray options as a massaging showerhead at less cost. Bathe in a swimsuit or install a privacy screen. Place a stake or pole as the hose stand until newly planted trees grow tall enough to hang it from. Create an optional porous deck to stand on using a wooden pallet or paving stones. The deck, plus thoroughly applied mulch, will eliminate muddy feet. In cold climates this could be installed in a greenhouse. See figs. 12.25 – 12.28 for a few outdoor shower and bath options, and search "Outdoor Showers Harvesting Greywater" at HarvestingRainwater.com for more.

Fig. 12.25. Low-cost outdoor tree shower without drainpipe. If your water pressure is high, you may need to wire or tie the hose to the branch.

Fig. 12.26. Outdoor bath directing its greywater via white and black pipe to the citrus tree, which also receives roof runoff from brown downspout pipe. Tree has since grown to create a living screen. Hot and cold bath water comes from old washing machine hook up in half wall.

Fig. 12.27. Outdoor shower schematic. Concrete platform can be designed to drain water to basins via pipes or to drain water off the edge to adjoining basins.

Fig. 12.28. Multi-drain pipe system for an outdoor shower. Three drains each divert greywater to different plantings in the landscape. You can selectively place rubber drain covers to direct greywater to a specific drain, as seen here, or remove the drain covers so the flow is distributed evenly between the three level drains.

A MULTI-DRAIN SYSTEM FOR WASHING MACHINES

Multiple drain pipes placed beside the washer each direct greywater to a different mulched basin within the landscape (figs. 12.29A, B, and chapter 5 in Volume 1). This is my favorite washing machine greywater system. It allows for easy and convenient control over where the greywater goes without any expensive valves or special parts. Mark the pipes to show their destination (fig. 12.29A). Writing with permanent marker on a strip of white electrical tape makes a good label.

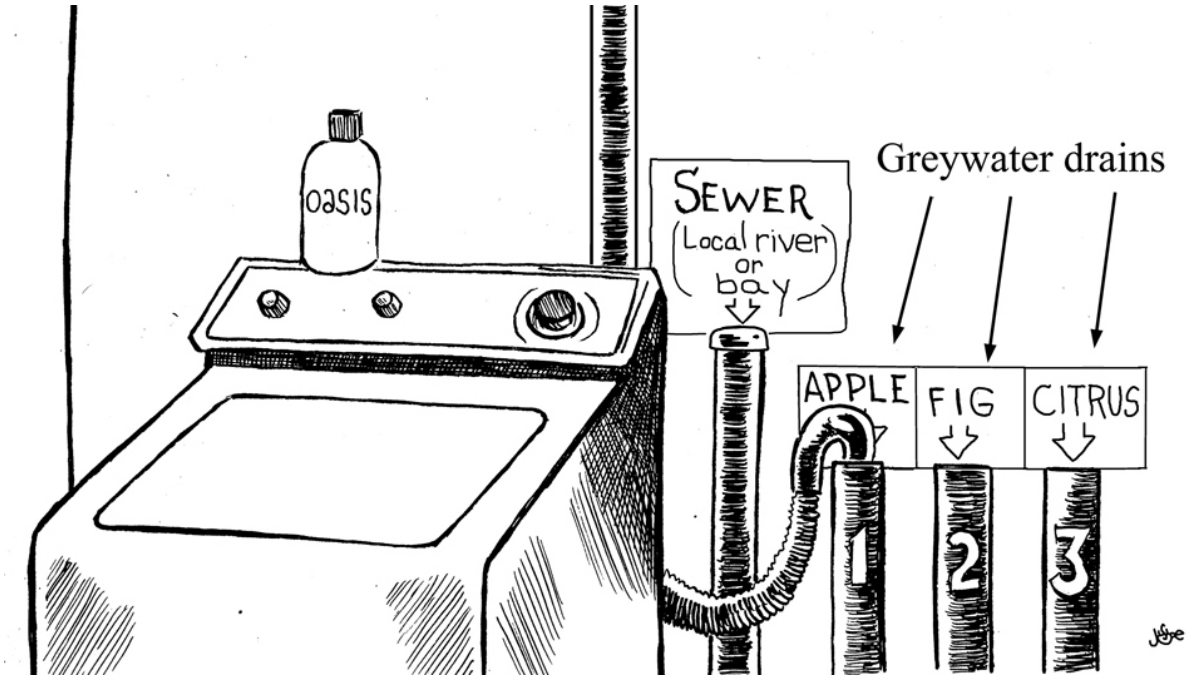


Fig. 12.29A. A multi-drain greywater system for washing machine. Greywater drains (marked with the fruit trees they water) are conveniently placed beside (not behind) the washing machine. Move the washer drain hose to a different pipe with every load of laundry. Note: The drain pipe going to sewer (capped when not in use) is an option for households that occasionally use non-biocompatible detergents or that have seasonally saturated or frozen soils. Text in parenthesis below "sewer" reminds us of where the greywater and detergents ultimately end up.

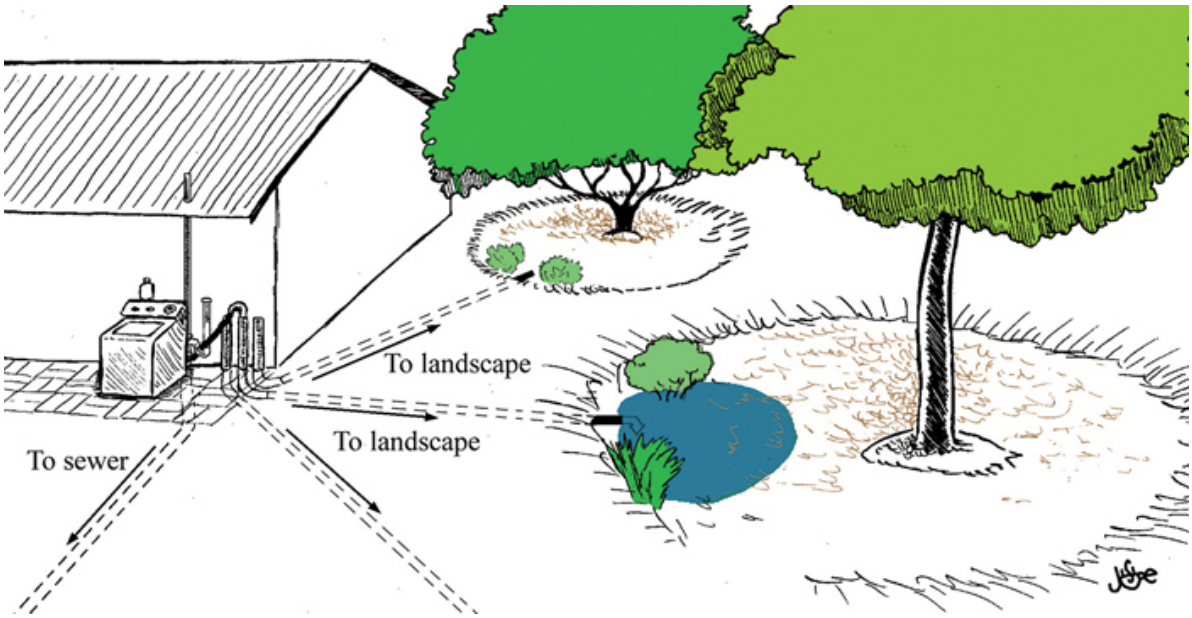


Fig. 12.29B. Expansion view of an outdoor washing machine in a non-freezing climate with a multi-drain greywater system distributing greywater to mulched and vegetated basins. Pipes maintain a minimum 2% slope. Note: Outdoor installations do not require P-traps or vent stacks for greywater drains, but they are required for the sewer drain.

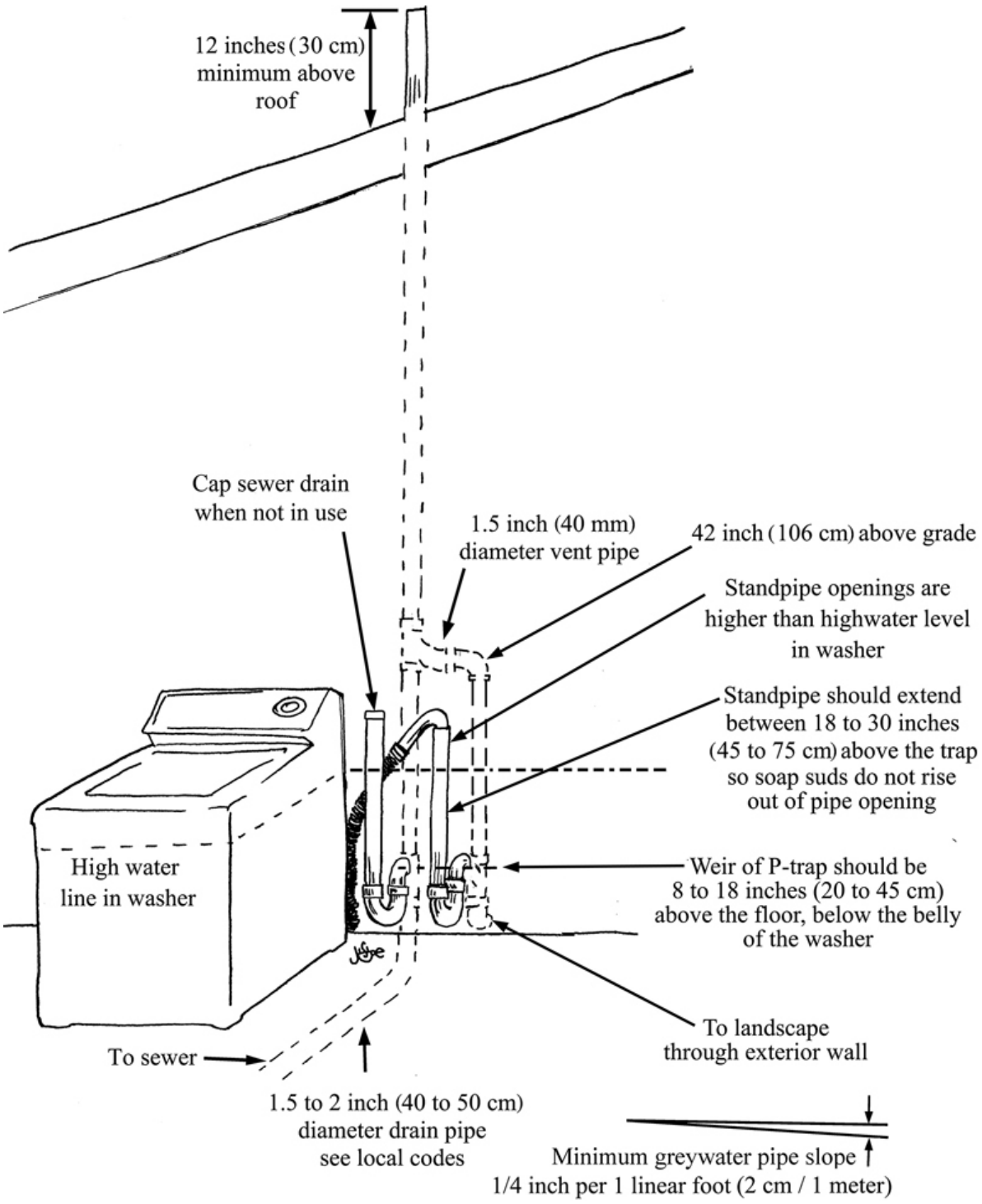

12 inches (30 cm) minimum above roof
Cap sewer drain when not in use
1.5 inch (40 mm) diameter vent pipe
42 inch (106 cm) above grade
Standpipe openings are higher than highwater level in washer
Standpipe should extend between 18 to 30 inches (45 to 75 cm) above the trap so soap suds do not rise out of pipe opening
High water line in washer
Weir of P-trap should be 8 to 18 inches (20 to 45 cm) above the floor, below the belly of the washer
To landscape through exterior wall
To sewer
1.5 to 2 inch (40 to 50 cm) diameter drain pipe see local codes
Minimum greywater pipe slope 1/4 inch per 1 linear foot (2 cm / 1 meter)

Fig. 12.30A. A multi-drain greywater system for washer located inside the home. Vent stack and P-traps are necessary to keep vermin and potential odors out of building. Note: Check with local authorities to see if a trap primer is required with this system. A *trap primer* occasionally injects a shot of water into seldom used P-traps to ensure there is always water in the trap—especially important for the drain to sewer. Or just cap sewer drain when not in use.

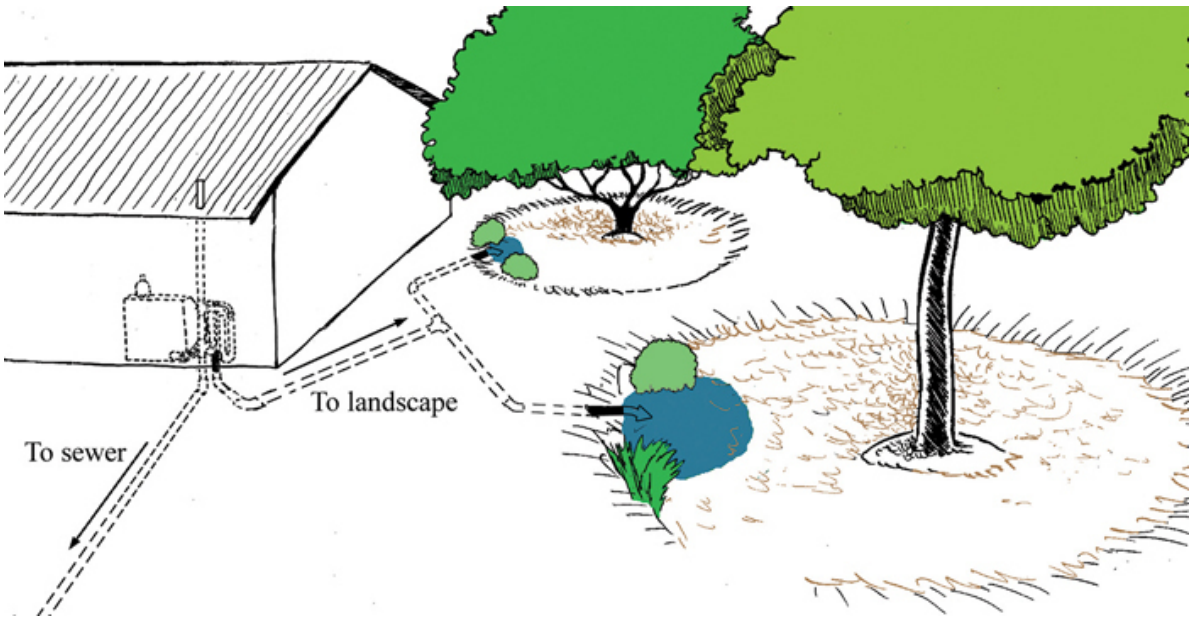


Fig. 12.30B. Expansion view of an indoor multi-drain greywater system with a single greywater drain pipe directing greywater outside to multiple basins/trees using a branched drain plumbing installation.

This multi-drain system can easily be set up for existing homes by cutting holes in an exterior wall to direct the greywater drains out to the landscape. If the washing machine greywater is inaccessible because the machine is in the core of a house on a concrete floor, consider moving the machine and its water and power hookups to a more accessible location, such as against an exterior wall. In new construction, install multidrain pipes in the laundry plumbing from the beginning. See the Real-Life Example section for more.

Note: If you want to direct greywater from your washing machine to areas above the machine, search "laundry to landscape" at OasisDesign.net for a system that uses the washer's pump to do this.

"BUCKET AND CHUCK IT"

Of all the greywater systems featured here, the "bucket and chuck-it" method is the quickest to install, the least expensive, requires no permit, can be set up and used by renters, and works great in buildings with or without yards or balconies. It directly connects you with your water use and greywater distribution—you see and carry what you use. That's why it's also the least convenient to use.

All you need is a bucket with a good sturdy handle. I prefer 5-gallon (20 liter) plastic buckets with metal handles (plastic handles break). You can often get barely used ones for free or cheap from grocery store delis, bakeries, or donut

shops. If you don't like to see greywater discoloring a white bucket, get a dark colored bucket.

Put the bucket in the shower to collect water as you wait for the water to heat up, and then stand over bucket while showering so most of the water draining or deflecting off you gets caught (fig. 12.31).

Fig. 12.31A. Bucket your shower's greywater

Fig. 12.31B. Chuck it to flush toilet or water plants

You can then flush your toilet with the bucket water, rather than flushing with the drinking water plumbed to your commode. When you want to flush, simply pour the bucket water into the toilet bowl, not the tank—slow and steady—so nothing hops out. Once the water reaches a certain level in the bowl it will self-flush via gravity.

HAND PUMP AND SIPHON SYSTEM

If your tub or shower is beside an exterior wall, but the drain pipe is inaccessible (within or below a concrete floor), this system enables you to access your shower or bathtub greywater and drain it directly outside through a hole and pipe constructed in the exterior wall. To use this system, you plug your shower/bath drain. Then use a hand pump, which you pump a few times to create the siphon effect, to move the water through the pipe to the landscape outside. All the water from a five-minute shower can be drained out to the landscape in ten minutes or less (fig. 12.32).

12.32. A hand pump primes a siphon to drain the grey-water through a hole and pipe in the exterior bathroom wall, carrying greywater to mulched and vegetated basins outdoors.

Search "Hand Pump & Siphon System" at HarvestingRainwater.com for all the details and examples of different systems.

KITCHEN RESOURCE DRAINS

For years my brother and I have been putting food waste, including grease, into a sink-side compost container (fig. 12.33), and safely and effectively recycling our kitchen-sink drain water using a branched-drain greywater system. It works well because we do not send grease down the drain or use a sink garbage disposal.

Fig. 12.33. Food caught in the wire screen of a kitchen sink is emptied into the compost bin or fed to chickens. Food waste becomes a resource, and kitchen-sink dark greywater is much cleaner.

Folks who want to maximize water conservation may be able to augment their greywater-harvesting system with kitchen-sink drain water if they live in a location where regulations allow this. The Arizona Department of Environmental

Quality's (ADEQ) definition of greywater does not include wastewater from a kitchen sink or dishwasher. However, with additional treatment, kitchen wastewater can be legally harvested in Arizona. If certain criteria are met, one allowed method of treatment in Arizona is the Kitchen Resource Drain (KRD) (fig. 12.34).

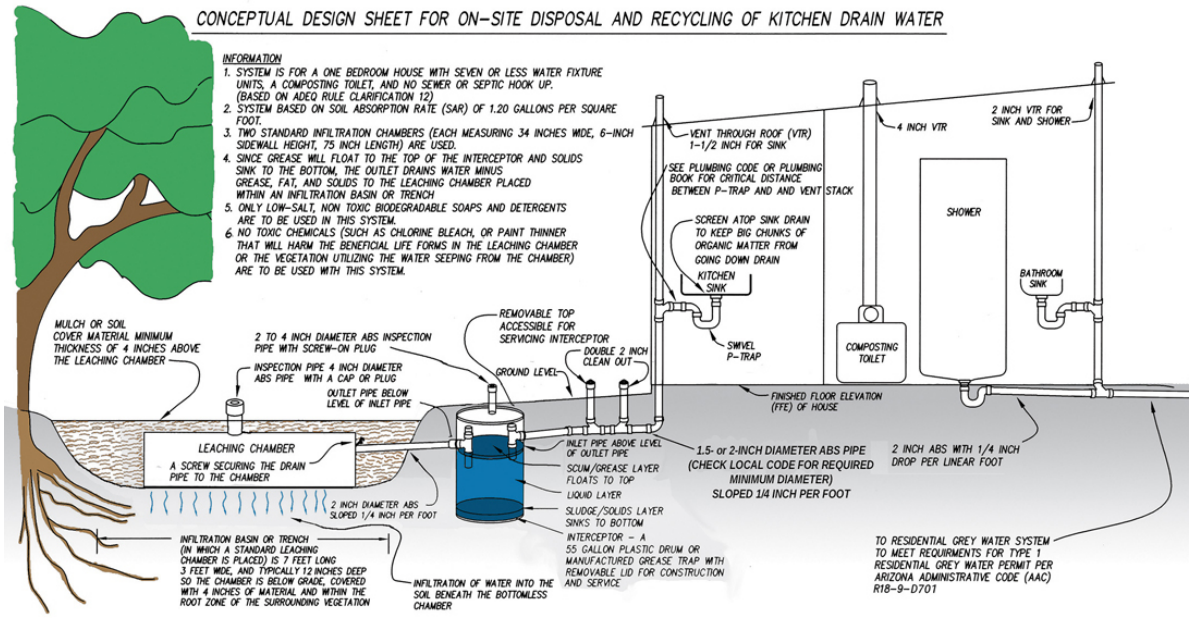

CONCEPTUAL DESIGN SHEET FOR ON-SITE DISPOSAL AND RECYCLING OF KITCHEN DRAIN WATER
INFORMATION
1. SYSTEM IS FOR A ONE BEDROOM HOUSE WITH SEVEN OR LESS WATER FIXTURE UNITS, A COMPOSTING TOILET, AND NO SEWER OR SEPTIC HOOK UP. (BASED ON ADEQ RULE CLARIFICATION 12)
2. SYSTEM BASED ON SOIL ABSORPTION RATE (SAR) OF 1.20 GALLONS PER SQUARE FOOT.
3. TWO STANDARD INFILTRATION CHAMBERS (EACH MEASURING 34 INCHES WIDE, 6-INCH SIDEWALL HEIGHT, 75 INCH LENGTH) ARE USED.
4. SINCE GREASE WILL FLOAT TO THE TOP OF THE INTERCEPTOR AND SOLIDS SINK TO THE BOTTOM, THE OUTLET DRAINS WATER MINUS GREASE, FAT, AND SOLIDS TO THE LEACHING CHAMBER PLACED WITHIN AN INFILTRATION BASIN OR TRENCH
5. ONLY LOW-SALT, NON TOXIC BIODEGRADABLE SOAPS AND DETERGENTS ARE TO BE USED IN THIS SYSTEM.
6. NO TOXIC CHEMICALS (SUCH AS CHLORINE BLEACH, OR PAINT THINNER THAT WILL HARM THE BENEFICIAL LIFE FORMS IN THE LEACHING CHAMBER OR THE VEGETATION UTILIZING THE WATER SEEPING FROM THE CHAMBER) ARE TO BE USED WITH THIS SYSTEM.
VENT THROUGH ROOF (VTR) 1-1/2 INCH FOR SINK
4 INCH VTR
2 INCH VTR FOR SINK AND SHOWER
SEE PLUMBING CODE OR PLUMBING BOOK FOR CRITICAL DISTANCE BETWEEN P-TRAP AND AND VENT STACK
SHOWER
SCREEN ATOP SINK DRAIN TO KEEP BIG CHUNKS OF ORGANIC MATTER FROM GOING DOWN DRAIN
KITCHEN SINK
BATHROOM SINK
SWIVEL P-TRAP
COMPOSTING TOILET
MULCH OR SOIL COVER MATERIAL MINIMUM THICKNESS OF 4 INCHES ABOVE THE LEACHING CHAMBER
2 TO 4 INCH DIAMETER ABS INSPECTION PIPE WITH SCREW-ON PLUG
REMOVABLE TOP ACCESSIBLE FOR SERVICING INTERCEPTOR
DOUBLE 2 INCH CLEAN OUT
INSPECTION PIPE 4 INCH DIAMETER ABS PIPE WITH A CAP OR PLUG
GROUND LEVEL
OUTLET PIPE BELOW LEVEL OF INLET PIPE
FINISHED FLOOR ELEVATION (FFE) OF HOUSE
LEACHING CHAMBER
A SCREW SECURING THE DRAIN PIPE TO THE CHAMBER
INLET PIPE ABOVE LEVEL OF OUTLET PIPE
1.5- or 2-INCH DIAMETER ABS PIPE (CHECK LOCAL CODE FOR REQUIRED MINIMUM DIAMETER) SLOPED 1/4 INCH PER FOOT
2 INCH ABS WITH 1/4 INCH DROP PER LINEAR FOOT
SCUM/GREASE LAYER FLOATS TO TOP
LIQUID LAYER
2 INCH DIAMETER ABS SLOPED 1/4 INCH PER FOOT
SLUDGE/SOLIDS LAYER SINKS TO BOTTOM
INFILTRATION BASIN OR TRENCH (IN WHICH A STANDARD LEACHING CHAMBER IS PLACED) IS 7 FEET LONG 3 FEET WIDE, AND TYPICALLY 12 INCHES DEEP SO THE CHAMBER IS BELOW GRADE, COVERED WITH 4 INCHES OF MATERIAL AND WITHIN THE ROOT ZONE OF THE SURROUNDING VEGETATION
INTERCEPTOR - A 55 GALLON PLASTIC DRUM OR MANUFACTURED GREASE TRAP WITH REMOVABLE LID FOR CONSTRUCTION AND SERVICE
INFILTRATION OF WATER INTO THE SOIL BENEATH THE BOTTOMLESS CHAMBER
TO RESIDENTIAL GREY WATER SYSTEM TO MEET REQUIRMENTS FOR TYPE 1 RESIDENTIAL GREY WATER PERMIT PER ARIZONA ADMINISTRATIVE CODE (AAC) R18-9-D701

Fig. 12.34. Kitchen Resource Drain. Credit: Drawn by Bill Cunningham P.E., Southwest-Solar.com

ADEQ has approved permits using the KRD for progressive new homes built with a composting toilet (a current prerequisite for the KRD), and no sewer or conventional septic tank hookup (though the code should be changed to allow the KRD with or without a composting toilet). Both the KRD and a separate ADEQ-approved branched-drain greywater system for washers, showers, bathtubs, and non-kitchen sinks were used in these progressive new homes. This approach saved the owner-builders money, conserved water, and turned all wastewater and human waste into on-site resources.

General components

The unique element of the KRD is the *interceptor*, which acts like a mini-septic tank that allows grease to float to the top, solids to sink to the bottom, and clearer water to flow out of the middle of the interceptor barrel. This water then flows to *subsurface leaching chambers* (also known as *outlet chambers*) where the water supports vegetation in the landscape. The interceptor is hooked up to the kitchen-

sink drain pipe just outside the house. Because of the interceptor, the KRD is more complex than other greywater systems and has *higher* maintenance requirements.

The interceptor can be constructed on site using either a 55-gallon (200-liter) plastic storage barrel (metal will rust) for single-bedroom residences, or a multiple-barrel system or larger manufactured grease trap for larger homes with greater water volumes. The interceptor is installed vertically with a removable lid and a capped inspection pipe so accumulated solids can be emptied periodically, as occurs with a standard septic tank.

Only direct kitchen-sink drain water to a KRD. If you were to direct household grewyater to the KRD, you'd have to increase the size, cost, and maintenance of the interceptor.

For more detailed sizing and implementation information on the KRD see appendix 3, and see the Real-Life Examples below.

REAL-LIFE EXAMPLES

REUSE VIA COMPOSTING TOILETS AND GREYWATER HARVESTING VERSUS DISPOSAL VIA SEPTIC TANKS AND SEWERS—ARIZONA

A growing number of people are designing, building, and living in fully permitted homes that do not have conventional wastewater systems. Rather than generating wastes, these folks generate resources. They do so by recycling all the greywater and dark greywater within their landscapes, and by safely composting and transforming all *humanure* into a natural and safe soil amendment using a compost toilet (boxes 12.15, 12.16). The waterless compost toilet ends the practice of defecating into a toilet flushed with drinking water. They stop crapping in the water cycle, and instead reinvest their nutrients (box 12.17) in the carbon cycle. Additionally, the compost toilet avoids the cost and land disturbance of a conventional septic tank.

All the greywater that sustainable-home designer Barbara Rose (BeanTreeFarm.com) generates in her beautiful Pima County, Arizona, home is recycled in her verdant landscape, consistent with Arizona Administrative Code (AAC) R18-9-D701 (fig. 12.35). According to the code, if residential discharge of greywater is less than 400 gallons (1,514 liters) per day and meets the 13 requirements of the rule, a residence is automatically considered to have a general

permit for reuse of greywater. Thus the greywater from Barbara's bathroom sink and shower is legally distributed directly to her landscape via a branched-drain system.

Fig. 12.35. Barbara Rose's garden watered with a KRD and harvested rainwater. Bean Tree Farm, Tucson, Arizona

The exception to the general permit is drain water from a kitchen sink, dishwasher, and toilet—all of which the state classifies as blackwater, which must be disposed of or permitted for reuse in a different way than greywater. Barbara has no dishwasher (see box 12.13) and uses a waterless compost toilet instead of a flush toilet. Her kitchen sink drain water is directed to the landscape via a Kitchen Resource Drain (KRD)—see the Variations section and appendix 3 for implementation information (box 12.14).

Box 12.13. Automatic Dishwashers and the Kitchen Resource Drain (KRD)

The drain water from automatic dishwashers can be harvested within a kitchen resource drain (KRD), but dishwasher drain water is typically a poor greywater source. Art Ludwig reports in *The New Create an Oasis with Greywater* that it is high in salt and has a high pH due to conventional automatic dishwashing compounds. He also reports that alternative

cleaners do not work well in dishwashers.[19] Instead wash your dishes by hand with milder soap, harvest that kitchen sink drain water, and forgo the cost of a dishwasher.

Box 12.14. How to Obtain a Permit for a Kitchen Resource Drain (KRD) and Composting Toilet in Arizona

To obtain a permit for a Kitchen Resource Drain (KRD) and composting toilet in Arizona, do not use the term "KRD." Instead refer to the whole system as "an on-site wastewater treatment system with composting toilet, interceptor, leaching chamber(s), and greywater reuse"—terms staff members at the Arizona Department of Environmental Quality are more familiar with.

To obtain a permit in Pima County, Arizona, fill out and submit "R18-9-E303. 4.03 General Permit for Composting Toilet" to the Pima County Department of Environmental Quality, and pay the fee of $500. The fee is $1,000 if your Arizona county does not have delegation authority, in which case the Arizona Department of Environmental Quality handles the permit, rather than your county. If the residence is within 200 feet (61 meters) of an existing sewer, apply for a waiver from hooking up to the sewer ($25). Submit the specification sheet and owner's manual for the approved proprietary composting toilet, or approved compost toilet referenced design, along with the permit application.

Barbara installed a proprietary, or commercially manufactured, Biolet-brand composting toilet, whose retail price starts at close to $3,000. A less expensive option at about $800, is a Barrel Compost Toilet kit designed by David Omick (Omick.net), which Arizona now permits as an approved compost toilet referenced design (available from Watershed Management Group [WatershedMG.org]). A site-built Masonry Chamber Composting Toilet is also now permitted in Arizona.

See appendix 4 and box 12.15 for more composting toilet resources, and search "Legalizing Compost Toilets" at HarvestingRainwater.com.

Box 12.15 Considerations When Selecting a Composting Toilet

When considering a composting toilet for your home, in addition to cost, use and maintain a variety of systems at other people's houses or businesses before you buy one to see what you are willing to do and how different systems work with your aesthetics. Conventional toilets flush our deposits "away," whereas composting toilets require you to actively participate in the composting process. The stages and degrees that you need to be involved with in the composting process vary depending on the type of composting toilet.

Make sure you choose a system sized to handle expected volumes. Colder climates may require larger systems, since the composting process slows as temperatures drop. The system must be large enough to store winter deposits until temperatures are warm enough to reactivate a more robust composting/decomposition process. Composting temperatures can be increased by more active participation in the composting process, such as ensuring the composting material has the right ratio of carbon to nitrogen, is of adequate volume, is properly aerated, is covered, and has the right moisture content (box 12.16).

Box 12.16. The Influence of Time and Temperature on the Composting Process

There are a number of different types of composting toilets using different means of composting. What is important is that the composting process is completed before the toilet's composted materials are put to use elsewhere. Thus, the Washington State Department of Health publication, *Water Conserving On-Site Wastewater Systems: Recommended Standards and Guidance*, states that four temperature ranges should be recognized when considering the composting process:

- Below 42˚F (5.6˚C) – little to no active microbial processing takes place. Within this temperature range, the system will serve only as a storage vessel for excrement, toilet paper, and additives.
- From 42˚F (5.6˚C) to 67˚F (19.4˚C) – psychrophilic microorganisms dominate (e.g., actinomycetes and fungi), which results in a moldering processing. Moldering toilets are designed to operate within this temperature range. Because the composting process is so much slower in this range, larger composter-vessel sizes may be needed to compensate for the slow volume reduction of the composting mass.
- From 68˚F (20˚C) to 112˚F (44.4˚C) – mesophilic bacteria dominate. This is the typical temperature range for most composting toilets.
- From 113˚F (45˚C) to 160˚F (71.1˚C) – thermophilic bacteria dominate (atypical of most compost systems unless assisted by an external heating system or well managed/turned/moistened by user).

Note: Joseph Jenkins has popularized a system based on aerobic, thermophilic composting in his book *The Humanure Handbook*, wherein he states, "Complete pathogen destruction [by composting] is guaranteed by arriving at a temperature of 62°C (143°F) for one hour, 50°C (122°F) for one day, 46°C (114.8°F) for one week, or 43°C (109.4°F) for one month."

For more information on composting toilets, see appendix 4.

Box 12.17. Potential of Our Own "Wastes"

Urine is relatively sterile (meaning it has a very low risk of transferring disease) though it is high in nutrients...

Every year, each adult produces via their urine:

- 9 pounds (4 kg) nitrogen
- 0.8 pounds (0.36 kg) phosphorus
- 2.2 pounds (1 kg) potassium

Enough to fertilize 3,000 - 4,000 square feet (278 m^2 – 371m^2) of crops[20]

I pee while I'm showering if I'm using a grey-water-harvesting shower since I know the greywater will dilute the salt of my urine, then the drain will beneficially deliver all those nutrients to living soil and the roots of plants.

This increases the value of the organic mulch in the greywater-harvesting basin, because the fertilizing effect of urine—just as that of chemical fertilizers—is greater when there is more organic matter in the soil.

Fully composted humanure (not uncomposted feces) could be a source of that organic mulch, and additional nutrients…

Human feces is:

- 66% moisture

- 5-7 % nitrogen
- 5.4% phosphorous
- 2.5% potassium[21]

The above information is meant to open your eyes to the potential of other on-site "wastes" that could be resources if they are managed differently.

As farmer/author Gene Lodgson points out, it has taken us about 100 years with poor agricultural practices to reduce soil organic matter to dangerously low levels—from about 5 percent on average to below 2 percent—and experts say it might take at least that long to build them back up again using organic methods on a large scale.[22]

The following is a 2020 cost comparison between compost toilet/greywater reuse/KRD systems and more conventional wastewater disposal options for a one bathroom, one bedroom home in Pima County, Arizona:

Method 1: Greywater to the landscape. Kitchen sink drain water to a Kitchen Resource Drain (KRD). And a compost toilet.

Composting toilet:	$800 to $300
Backhoe digging of site-suitability (percolation) test for KRD outlet chamber field:	$350 to $45
Permit review fees:	$50
Waiver for not hooking up to sewer:	$2
On-site greywater-disposal system including a three-way diverter valve (not including labor):	$50
On-site kitchen resource drain (KRD) (not including labor):	$50

TOTAL COST: $2,675 to $4,975, or more

Note: with no sewer hook up there is no monthly sewer bill

Method 2: Conventional septic system

Backhoe digging of site-suitability (percolation) test hole for leach field:	$150
Permit review fee:	$45
In-house drain pipe (not including labor):	$40
Septic tank, leach field, and installation:	$8,000 to $9,000, or more

TOTAL COST: $10,350 to $11,350, or more

Note: with no sewer hook up there is no monthly sewer bill

Method 3: Hookup to existing sewer abutting the property

Sewer Connection

Permit fees:	$4,200 to $5,000
Installation and connection of 4-inch (100-mm) sewer pipe to the municipal sewer line: (price will be *much* higher if there is no existing sewer line abutting your property)	$4,000 to $6,000
In-house drain pipe (not including labor):	$400
TOTAL COST: $8,600 to $11,400, or more	

Costs in Arizona will vary with site location, local regulations, and material selection.

GREYWATER HARVESTING HELPS CREATE A FIRE-RESISTANT OASIS— CENTRAL ARIZONA

Brian Thacker of Arizona Renewable Resources was prowling Google Earth, studying the satellite images of the catastrophic Rodeo-Chedeski fires of June 2002, when he came upon something amazing. There in the middle of a charred landscape of burned pine trees he saw two green areas surrounding two undamaged homes—thriving oases amidst devastation. He had to know why these homes were spared a fiery end, and called up the area fire marshal to investigate. He found the homeowners did two key things.

First, they used fire-defensive practices in their landscape. Within a 50- to 75-foot (15-to 23-m) radius around their homes they removed all ground-ladder fuels that could spread a low-burning fire into the canopy of trees and shrubs. They pruned tree branches up 4 feet (1.2 m) from the ground; cleared, chipped, and shredded dead limbs and brush; spread the resultant mulch over the soil to retain soil moisture; removed conifers and shrubs right next to or against the house; and cleared pine needles from the roof and gutters.

Second, the homeowners directed their greywater into the surrounding landscape, particularly the oasis zone around their homes. This supplied the native vegetation with enough moisture to keep it from igniting so it acted like a firebreak around the homes.[23] See appendix 4, for more information on designing for fire prevention.

THREE GREYWATER-HARVESTING, FOOD-PRODUCING LAUNDROMATS— TUCSON, ARIZONA

A Backyard Laundromat Shared with Neighbors on the Block

My brother Rodd and I have long had a multidrain greywater system for our washing machine (figs. 12.28, 12.29) to help irrigate our fruit trees and edible cactus, but we didn't do enough laundry to keep our plants thriving and fruiting in the dry months. Then it dawned on us that many neighbors washed their clothes in laundromats where greywater was sent wastefully down the sewer. Perfect!

We approached environmentally minded neighbors and proposed a deal. They could use our washing machine at the same price per load as the laundromat if they used detergents we approved of (see box 12.5). They no longer had to leave the neighborhood to do their laundry and they could harvest fruit from the trees irrigated with their clothes washings (fig. 12.36)! And as a bonus, our home and washing machine are solar powered, reducing the pollution-generating use of municipal electricity generated by burning coal or natural gas. We used the laundry proceeds to maintain the system.

Fig. 12.36. Rodd eating the white sapote fruit grown with harvested rainwater and greywater.

With three to seven households using our system, we dramatically reduced supplemental irrigation with municipal drinking water, we strengthened

community ties, and our neighbors shared their water conserving/harvesting experiences with others. A whole lotta feel good!

An Apartment Complex Laundromat that also Created a "Well" of Filtered Water, a Community Hub, and More

A common "wash and well" was created when nineteen members of Sitting Tree —an urban community of apartment dwellers—pooled $1,750. They installed a laundry shed, efficient horizontal-axis washing machine, outdoor shower, homemade solar water heaters, Oasis 4-stage reverse-osmosis water filter (the "well"), clothesline, and compost bins. Fruit trees, grapes, a catclaw vine, a native shade tree, and garden plots are now watered by greywater harvested from the washer, the water filter, and the outdoor shower. None of the community members could afford the system on their own, but together it was easy. One system, rather than nineteen, serves them all. Households paid 50 cents for each load of wash, which paid off their self-loan in five years. They've since dropped the cost for each load of wash to 25 cents per load, which covers maintenance costs and raises money toward buying the next washing machine when the old one needs to be replaced. After twenty-four years with the system, they are now on their third washing machine. Furthermore, the "wash and well" has become a thriving gathering spot strengthening community ties through interaction, cooperation, conversation, jokes, and play. See figs. 12.37A, B, C.

Fig. 12.37A. Wash and well, front view. The batch-style solar water heater on compost bins heats water for the outdoor shower behind the vine-covered wall. The solar water heater atop the laundry shed roof is for the washing machine. An old refrigerator is used for the heater's insulated box. Its door is closed to hold in heat at night, and then opened in the morning to let in the sun.

Fig. 12.37B. Wash and well, back view. Tom is at the "well" filling his water jug from the faucet of the reverse-osmosis water filter, which is located behind the corrugated metal. Chet folds laundry dried by the solar clothes drier (clothesline) in the foreground.

Fig. 12.37C. Multi-drain greywater system for washer and water filter. The drain tube taped to the washing machine drain hose conveys backwash water from the reverse-osmosis filter. The joined hoses are moved to a different greywater inlet pipe with each load of wash.

A Co-Housing Version on a Larger Scale, and How to Adapt to Change

Stone Curves Co-Housing Community in Tucson did something similar, but different. They have 48 households and three community washing machines (some private units also have their own washing machine). Initially, there were supposed to be four community washing machines. One machine was to permanently send all its drain water to the sewer, and was to be labeled for washing diapers, greasy clothes, and anything else washed with strong detergents or chlorinated bleach that you would not want on the landscape. But in the end, only three community washing machines were obtained. The first machine (with the easiest access to multi drains—one drain to landscape and one drain to sewer) can handle all the nasty laundry when its drain hose is in the sewer drain. When this washer gets cleaner laundry its drain hose is switched to the landscape drain and the community orchard.

So this machine, plus the other two machines, each send greywater to its own branched drain system (similar to fig. 12.30). Each system irrigates four fruit trees, for a total of twelve greywater-irrigated fruit trees in the community orchard. A laundry map shows which trees are watered by each machine.

The system worked well for over 15 years, but three issues eventually arose, which are described below, along with potential solutions.

Issue one: As more synthetic-fibered clothes were washed in this high-volume system, small alluvial fans of lint began to form at the pipe outlets (fig. 12.38). Greywater would sometimes pool on top of the lint, and algae would sometimes grow on the lint. This was particularly noticeable in the easternmost system, which was likely irrigated from the washing machine that had the highest use.

Fig. 12.38. Alluvial fan of lint accumulating on top of mulch. Lint comes from the community laundry greywater outlets.

Solution options:

1. Filter out the lint at the washing machines drain hose outlet before it enters the greywater pipe. Search online for multiple filtering options. Consider purchasing natural-fibered clothing as synthetic clothing is replaced.
2. At least once a month, remove the accumulated lint at the greywater pipe's outlet to the mulched basin using a pitchfork, rake, and/or gloved hands. Throw lint away and roughen up and loosen soil and mulch using a rake to increase infiltration rates.
3. Since water pooling on the lint may indicate too much water is being released to too few outlet points, add flow splitters to the branched-drain system starting by doubling the current number of outlets.

Issue two: There has been a significant drop in use of the shared laundry, and thus in the greywater volume sent to trees. There are multiple reasons for this. The first wave of kids who lived here has grown up, so units that used to have four or more

people now have only one or two people. Some folks have installed washing machines in their own homes and no longer use the community laundromat. Two of the community washing machines are leased from a company that is slow to provide repairs or replacement, so machines can be out of service for a whole month with no grey-water irrigation going to the machine's branched-drain system and its trees. As a result of all these factors, some trees in the laundromat orchard have died due to drought stress.

When there is not enough greywater going to the orchard, a community volunteer needs to notice this and water the trees by hand from rainwater cisterns or—once the cisterns are empty—from the city water supply. Residents share the water bill, and some want the supplemental watering with city drinking water reduced to save money.

Solution options:

1. Realign greywater outlets from basins where fruit trees have died due to drought stress to mulched basins where fruit trees are still living to increase the greywater supply to these remaining trees. Plant low-water-use native plants that produce edible seeds and pods in place of the dead fruit trees.
2. Encourage those using washing machines at home (where the greywater goes to the sewer) to use the community laundromat so their greywater goes to the orchard.
3. Rework the contract with the washing machine leasing company to ensure repair or replacement occurs within a week or less.

Issue three: Sometimes, after finishing laundry using caustic detergents in the first washing machine (the one with multiple drains—one to the sewer, one to the landscape), people forgot to put that washer's drain hose back to the landscape drain when using appropriate detergents. As a result, the section of the orchard receiving that machine's greywater was more susceptible to greywater drought.

Solution option:

Purchase a fourth washing machine as originally planned, and dedicate its use for non-greywater compatible laundry; thereby leaving the other three machines to more reliably direct their greywater to all sections of the orchard.

AN ABUNDANT SPRING OF AIR CONDITIONING CONDENSATE WATER HARVESTED WITH ADDITIONAL DISCARDED WATERS—TUCSON, ARIZONA

The Underwood Family Sonoran Landscape Laboratory at the University of Arizona is one of my favorite oases in the built environment. It was designed by Ten Eyck Landscape Architects and is located on the south and east sides of the College of Architecture, Planning, and Landscape Architecture (CAPLA) building. Leaving the exposed solar oven-like parking lot, you walk into a cool sanctuary of living classrooms and hang out spots beneath a canopy of abundant shade trees and diverse life. And all this is supported almost entirely by "wastewater" harvested from adjoining buildings.

On average, 85,000 gallons (322,000 liters) of rainwater a year enters the landscape from the roofs of adjoining buildings. More surprisingly, 95,000 gallons (360,000 liters) of air conditioning condensate a year comes to the landscape from the HVAC (heating, ventilation and air conditioning) units on these roofs, despite Tucson's dry climate (fig. 12.39). The perspiring, respiring bodies of many students and professors inhabiting the buildings increase the moisture in the recirculating air, which the HVAC systems capture.

Fig. 12.39. The CAPLA living classroom. Air conditioning condensate overflows from the cistern into the pond supporting native vegetation and endangered fish and frogs.

Additionally, the landscape harvests backwash water from the daily maintenance of an adjoining sand filter well (about 200 gallons [760 liters] per day) and greywater from the building's drinking fountains. Sink greywater is not captured because students doing studio design projects might unconsciously pour toxic solvents, paints, or glues down sink drains.

An 11,600-gallon (43,900-liter) cistern captures some of these waters, while the rest—along with overflow from the cistern—is captured by a small pond and arroyo-like swale meandering through much of the landscape.

Five biomes of the Sonoran Desert—wetland, canyon, riparian, mesquite bosque, and upland Sonoran—are represented by microclimate groupings of native plant species. Endangered Gila topminnows and lowland leopard frogs are raised in the wetland's pond. Great blue herons, roadrunners, and hawks visit to partake of the bounty. Students can eat wild grapes, chuparosa flowers, and mesquite pods.

Most of the landscape's water needs (83 to 87%) are met by these on-site "wastwaters," though 100% could easily be met with a few small changes:

- Reduce water needs—replace a few high-wateruse plants, such as an Arizona sycamore, with a lower-water-use variety.
- Increase water supply—direct more runoff surfaces, such as a parking lot or another roof, to the landscape.
- More efficiently slow, spread, and sink the water within the landscape—direct cistern overflow to the highest point of the landscape (currently directed to the midpoint), which can then overflow to—and help irrigate—all points below. Create higher-capacity mulched basins within the swale and upland Sonoran biome to increase the amount of moisture captured in the soil before overflow water escapes.

Part of the vision of this biosponge-like landscape was to illustrate a new way of landscaping, creating a model for how to transform the campus and regional landscaping. Former associate dean Dr. Ron Stoltz, who oversaw the project, now wants to see the parking lot south of the CAPLA landscape transformed into the second-largest green space on campus, irrigated solely by discarded waters from adjoining rooftops, hardscapes, air conditioners, and greywater drains. You needn't look far to see that this works (fig 12.40).

Fig. 12.40. What landform does the parking lot and surrounding buildings resemble? A canyon. Just as the CAPLA landscape on left has been transformed into a verdant urban canyon, so the adjacent parking lot could be transformed to a biosponge oasis irrigated with water harvested from the surrounding buildings (mesa tops) and hardscape.

For more information about this project, see how its concrete *drainage*-way was transformed into a cobble *infiltration*way at the end of chapter 7.

HOW SAFE, EFFECTIVE, AND ACCESSIBLE RESIDENTIAL GREYWATER HARVESTING WAS LEGALIZED AND INCENTIVIZED IN ARIZONA

In the 1990s only two greywater harvesting permit applications were submitted to the Arizona Department of Environmental Quality (ADEQ). However, ADEQ estimated that during that period more than one hundred thousand people in the state were harvesting their greywater without a permit (predominantly via simple, inexpensive systems), in other words—illegally.[24] Change was needed.

At the time, ADEQ's permitting process was especially onerous and prescribed the use of relatively complex, expensive, high-maintenance systems.[25] While authorities knew that this permit was deterring folks from applying, they did not realize the full extent to which people were avoiding the process until seeing the results of the "Residential Graywater Reuse Study: The Good, The Bad, The Healthy." This study was conducted by the Water Conservation Alliance of

Southern Arizona (Water CASA), led by Val Little, in collaboration with University of Arizona researchers, ADEQ, the Pima County Department of Environmental Quality, and six southern Arizona water providers.[26]

The study gave authorities the data they needed to act, as it revealed just how many people were illegally harvesting their greywater without guidance, and how much water was potentially being saved through the reuse of that greywater.[27] Moreover, the study indicated that greywater posed a relatively low health risk if it is properly applied and managed.[28]

As a result of the study, it was decided:

- The public needed better guidance on how to safely discharge/reuse greywater;
- Greywater should be viewed as an alternative water source, not as a toxic discharge that needed to be mitigated (such as blackwater in sewage or septic systems); and
- There needed to be an equitable way for the tens of thousands of non-permitted, legacy greywater users to continue to use greywater without requiring expensive, complex systems or permitting conditions.[29]

So, ADEQ adopted new regulations in 2001 that embodied an educational approach focusing on providing guidance for existing and prospective greywater users. Education was then provided through ADEQ, Water CASA, non-profit organizations, water providers, greywater workshops, books such as this one, and other venues. The permit is now automatically granted, without requiring users to submit a permit application, as long as thirteen common-sense performance-based guidelines or best management practices are met. These guidelines were developed by ADEQ and Water CASA. New Mexico soon followed Arizona's lead in adopting this less onerous, more educational approach. Other states have adopted similar measures.

ADEQ's new approach ended the problem of tens of thousands of Arizona's greywater users being out of compliance, and not receiving guidance.[30] Enforcement of the new regulations is complaint-driven. For example if you see your neighbor's greywater pooling on the surface for days or flowing into your yard, you can notify ADEQ. ADEQ staff will then contact and educate the person on proper greywater use, ensuring compliance with the permit conditions.

This approach has enabled an ever-growing number of non-profit organizations and educators to provide the public with regularly scheduled greywater-harvesting

presentations and hands-on installation workshops on safe, effective, accessible, low-cost, low-maintenance systems that can now be legally installed. Simultaneously, a growing number of companies are providing services that design and install these systems.

And the greywater rules continue to evolve and improve based on the years of experience gained since the 2001 adoption of the rule revisions; the on-going work of dedicated ADEQ staff such as Chuck Graf; and the input from citizens, non-profit organizations, and practitioners. Effective January 1, 2018 further rule revisions were adopted to clarify some ambiguities and further expand the utility of the performance-based greywater permits, including such permits for larger scale greywater use.[31]

Performance-Based Codes versus Prescriptive Codes

In *The Water-Wise Home* (a great guide for grey-water harvesting and making policy change), author Laura Allen describes the difference between the two codes as follows,

"Performance-based codes describe health and safety requirements for greywater systems. Systems that meet the requirements are legal: those that don't are not. Performance-based codes typically don't require inspections or fees, yet provide legal grounds for a city to take action against a problem system. For example, "no pooling or runoff" is a common guideline that prevents exposure to greywater, but many codes don't specify how to meet this requirement. Performance-based codes are written in simple, straightforward language. States and local jurisdictions can provide further guidance, such as how to size a system to avoid pooling and runoff, but the more specific details are left out of the code.

Prescriptive codes specify exactly how to build a greywater system including what materials and parts can be used. Instead of stating, "No pooling or runoff allowed," they may estimate greywater production based on number of bedrooms in the house (*as a means of predicting how many people live in the home and send greywater down the drain*) and size the irrigation area based on soil type."[32]

I typically prefer performance-based codes (such as the ADEQ greywater guidelines adopted in 2001) because I find them more conducive to innovations that continually evolve and improve the systems. Performance-based codes clearly state the performance standards the system must achieve, without limiting your options to one or two prescribed systems. While, prescriptive codes specifying technological standards, materials, and systems often inhibit innovation and lead

to more complex—but often more expensive and not necessarily more effective—systems, as was the case in Arizona prior to 2001.

A system is only as good as the user's engagement with it and awareness of it. So make your systems simple; convenient to use; and easy to observe, understand, and maintain.

Epilogue

Be the change you want to see in the world.

—Gandhi

We all live in watersheds within watersheds; we are all neighbors of neighbors. Whether we are conscious of it or not, we are part of interconnected ecological and human communities. We live both upstream and downstream of our neighbors; what we do affects them and what they do affects us. This book is an invitation to recognize and rejoice in these connections, and to act now to improve life for everyone by starting right where we are. Having read this book (and Volume 1), you have the tools to establish a relationship with your watershed and beneficially harvest water. Now *do* it!

Once you've begun to live within your sustainable water supply and enhanced your piece of the community watershed, CONGRATULATIONS! You have proactively become part of the solution rather than the problem. Use the water-harvesting principles and ethics. Continually look for ways to improve your system. By setting an example you are planting a seed of abundance—because living by example is the most powerful tool for inspiring change. The more you actively share your learning and passion, the quicker the bounty will spread.

This book contains many water-harvesting options and examples to motivate and inspire you. For more techniques and ideas, seek out water-harvesting information around the world—particularly in climates similar to your own. Check out water-harvesting workshops, demonstration sites, literature, the web, videos, archaeological sites, and historical records. Learn more about your local ecosystem, climate, soils, history, and flora and fauna to work *with* the natural world. Build on successes and mitigrate failures— yours and other's—to leap frog to more effective ways to harvest rain. Join with friends to critique, improve, and learn from each other's efforts. And most important, celebrate everyone's efforts.

Remember, water harvesting is always site specific, so success depends on your growing site-observation skills—before, during, and after implementing the range of water-harvesting techniques you select. Water harvesting is a dynamic process

that enhances continually evolving *living* systems made up of billions of living organisms such as those within the soil, the vegetation, the wildlife, and the human community. As humans we can choose how we interact with the system. It's my hope—and the reason I wrote this book—that you will choose the path to sustainable abundance and you'll have fun shaking your rear end doing "a bun dance" along the way (fig. E.2).

Fig. E.1. The wasteful path to *scarcity*. The site rapidly dehydrates itself by erosively draining rainwater and runoff away to flood downslope areas and contaminate surface water with sediment. Greywater is lost to the sewer. Costly municipal or well water is pumped in to replace the free water that was drained away. Leaf drop/mulch is also drained away, further depleting fertility and water-holding capacity. This leads to a depletion of resources and feeling *scared in the city* due to the resulting *scarcity*.

Fig. E.2. The stewardship path to *abundance*. This site passively hydrates itself by harvesting, infiltrating, and bioremediating rainwater, runoff, and greywater on site; reducing downslope flooding and overall water consumption and contamination. The need to pump in water is greatly reduced or eliminated. Leaf drop/mulch is also harvested and cycled back into the soil and plants, further increasing fertility and water-holding capacity. This leads to an enhancement of resources and *a bun dance* of celebration due to the resulting *abundance*.

THE FUN AND EASY PATH TO ABUNDANCE

For me, finding and taking the path to abundance comes down to a few simple questions:

- What choice leads to more good for people and the earth?
- What choice makes things better both now and in the future?
- What choice gives back more than it takes from the living system?
- What choice leads to abundance for all?

The water-harvesting ethics (preface) and the concept of regenerative systems (chapter 1) can help answer these questions, but ultimately it's your powers of observation you should rely on. How might your proposed action lead to more good for people at home, in your community, and beyond, and for the ecological systems that sustain all life? How might it make things worse? Choose your course of action accordingly. Positive actions will be followed by many positive outcomes, like dominoes falling in a line.

Max O. Lindegger, a planner of sustainable communities around the world, describes choosing a path to abundance through adopting holistic, integrated design. The aim of such design, "is to allow everything to work together harmoniously, and you know you are on the right track when you notice that your solution for one problem has accidentally solved several other problems. You decide to minimize the use of automobiles in order to conserve fossil fuels, for example, and you realize this will also reduce air pollution, encourage healthful exercise, reduce noise, conserve land by minimizing streets and parking, multiply opportunities for social contact, beautify the neighborhood and make it safe for children."[1] As you have seen from stories and examples throughout this book, integrated water harvesting yields the same positive stream of outcomes.

A DROP IN THE BUCKET OF ABUNDANCE

Don't worry if your efforts seem small compared to the magnitude of regional, national, or global challenges. Many people stop themselves from moving forward by thinking their actions are just a drop in a bucket. But even one drop is great if it's a drop in the bucket of abundance. With enough drops we'll fill the bucket! A drop in the bucket is an issue only if it's a drop in the wrong bucket—the bucket of scarcity.

START NOW

"Gradualism is little more than escapism and do-nothingism, which ends up in stand-stillism."

—Martin Luther King, Jr.

We must achieve the character and acquire the skills to live much poorer than we do. We must waste less. We must do more for ourselves and each other. It is either that or continue merely to think and talk about changes that we are inviting catastrophe to make.

—Wendell Berry, from the essay "Word and Flesh," *What Are People For?*

The best time to plant a tree was twenty years ago, or today. It's the same with water harvesting and the interconnected pursuits of passive solar design, harvesting or producing local foods, and reconnecting with your Place and your community. These activities enable us to learn from, and work with, natural systems—do them now. Begin with long and thoughtful observation and keep on observing long into the future. Learning begins the moment we actively engage with our surroundings. Walk your site; become an observational sponge. What's naturally working? What's not? Why? How might you enhance what's working and change what's not working? Use the observation worksheets in appendix 5 of Volume 1 to record your thoughts. Go outside when it's raining—that's when you'll learn the most and have the most fun. When it's raining at my house I'm out in it, watchin', learnin', swingin' a shovel to redirect water flow, and lovin' it! If I'm at a friend's house when it rains I do the same thing, with my friend and me egging each other on.

Experiment and play with your observations. Don't let inexperience stop you from harvesting water. Get started. You will gain experience, make mistakes, and learn by fixing them. Always follow the eight water-harvesting principles and adhere to the three ethics. Using these will speed your learning process. Start at the top. Start small. Start! Your experience and learning will cross-pollinate to generate a whole new understanding of the system. Add critical thinking, and it becomes wonderfully delicious.

Is the east or west side of your home exposed to too much summer sun? Is there runoff you can use? If so, plant a tree within or beside a water-harvesting earthwork east or west of your home to shade out the sun. Then observe, and stay engaged. Does the tree suffer from too little water? How can you get more water to it? Is there room to expand the earthworks? Can you direct greywater to the earthwork? How can you reduce the tree's water needs? Mulch the earthwork? Swap it for a tree that uses less water? Is the tree in an ideal spot? If not, what would the ideal spot look like? Why? What other plants could benefit by being placed with the tree and earthwork? What other site-appropriate plants could produce more resources such as food? What potential production plants are missing or needed in your neighborhood? No sense in planting more pomegranates if your neighbor is overloaded with them. Plant something else, get to know your neighbor, and trade. Keep these questions and recommendations in

mind when placing other earthworks and planting other trees and understory vegetation. It will be easier each time, since you'll draw on what you learned before.

A PARTING VISION

The following is a weaving together—an integration—of real life experiences I've had in different communities around the globe. No one place had it all, but all places could have it all, and more. If we can imagine, if we can see, we can strive and act for it to be…

I arrive at this place for the first time and step outside beneath a canopy of leaves, blossoms, and fruit. The fragrant, cool air is delightful. I hear birds and insects sing from every direction. Looking and listening closely, I realize this is familiar in some ways, yet also unfamiliar—the plants and wildlife are unique to this place. There are natives and cultivars that have coevolved over millennia to meet the distinctive challenges and opportunities of this climate, soil, and people. They spark my curiosity. I stroll the path that slopes toward planting basins on either side—basins full of foliage and underlying sponges of rich organic matter.

I smile, realizing people here intentionally plant the rain along with the runoff from the path. The sound of flowing water and laughter pulls me in another direction, where I see a giggling mother and child playfully quenching their thirst from a drinking fountain. I also drink the water—its sweet! Could it be? A sign tells me it is so, with an illustration of how the building's roof runoff is captured in the nearby cistern, filtered, then directed to the drinking fountain via gravity. It invites me to look at how the overflow from the fountain's drain and the tank is directed to the sheltering, fruiting landscape irrigated solely with free, on-site waters—nothing is extracted from elsewhere or taken from others. And I get to eat some of the fruits. Delicious! I love this place!

My excitement grows as I cycle around the community alongside people of all ages and shapes who are cycling, walking, wheeling, running, and skateboarding—everyone enjoying continuous shade watered solely by street and path runoff. Here the streetscapes are like verdant parkscapes. You'd never know it was 100˚F (37˚C) in the full sun. What a beautiful day in a beautiful place! Every building is surrounded by its own unique oasis of different colors, shapes, and plant densities, each showcasing the distinct vegetative and aesthetic passions of its occupants. And each landscape is sustained by on-site waters that were once *thrown away*, but are now *reused today and every day*.

Everywhere I look, the built environment immediately shows me that people here understand the value of their limited water supply and how they strive to make the most of it by actively participating in—and modeling their built environment after—our planet's dynamic hydrologic cycle. Aided by living systems, they capture, reuse, and recycle fresh water again and again, improving its quality and quantity for all.

In the urban center of town, well-vegetated, water-absorbing public rights-of-ways widen, and the number of pocket parks increases, to offset the high density of adjoining multi-story buildings. Abundant runoff and drainwater from the buildings is harvested to support productive public food forests, readily accessible to people who have limited access to private yards and gardens. Everyone is embraced by this vibrant, food-producing, flood-abating outdoor life.

There are maps and apps guiding me to distinctive aspects of this community's watershed health renaissance including once-forgotten pre-historic water-harvesting trincheras, tinajas, and check dams; restored 100-plus year old step wells, swales, shelter belts, and cistern systems; rejuvenated natural swimming holes, grasslands, forests, and wetlands; along with especially dynamic examples of the new wave of water-harvesting sites.

In all the lands I pass through, crews energetically create and steward diverse water-harvesting earthworks and plantings along streets and medians; within residential yards, school grounds, parks, and common areas of office and apartment complexes; and throughout farmlands. The crews include volunteer neighbors, teachers, students, and scouts; municipal workers; and staff from local companies. As I stop to talk with them, I get to hear the roots of their enthusiasm….

"When I first heard about water-harvesting I didn't understand it. Then I saw my neighbor's system working in a storm. I tried it in my own yard, and was amazed by the results. Now, I'm out here to help amaze others!"

"I took the city's free water-harvesting class and plan to apply for their water-harvesting rebate, but first I'm refining my understanding by helping others with their water-harvesting projects, as I design my own."

"We're harvesting the water that's free, so there will be more shade, beauty, and food for you and me!"

"This is a 180° shift from how my company used to do things. We used to drain the rain, then install tons of plastic pipe to water plants with costly city water. But then my clients started asking for something different. They wanted me to "plant the rain." So I

took classes, read books, and got myself and my crews certified in water harvesting—and we get recertified each year to keep up with new techniques and practices. Now water harvesting, not "water draining" nor "water importing," is the foundation of all our landscaping. Our landscapes are healthier, our clients are happier, and we can't keep up with demand!"

"We're pulling excessive carbon from the atmosphere (where it's a liability) to living soil and vegetation (where its an asset) in a way that's got a great return on investment for all generations."

"By working together, as a neighborhood, rather than as individuals we get a lot more for a lot less. For example, look at the couple dozen public right-of-way water-harvesting installations just installed in front of our homes. Everything goes under one neighborhood permit—not many individual address permits. We get volume discounts on materials. Contractors do all area excavation and rock work at once saving them (and us) time and money. With the rain planted, neighborhood volunteer planting crews then come in to plant the vegetation within and beside the earthworks, and monthly stewarding parties keep it all looking great. Thus folks literally plant, join, and deepen roots in this community as they help each other. Land and people simultaneously transformed."

"When the city identifies a flooding problem, we go upstream looking for where the water came from in the first place. Then we get to work turning that "problem" water into "resource" water by infiltrating it into the soil to grow beautiful, verdant rain gardens as close as possible to where the rain falls. Planting the rain costs a fraction of what we used to pay to pipe it underground in stormdrains where it was out of sight, out of mind, and expensive as hell to find and fix. Thanks to water harvesting we're saving lots of money. Flooding has been dramatically decreased. Water quality has improved. Summer temperatures are cooler. Groundwater is recharging. Creeks are flowing clear again, year round, and salmon populations are rebounding."

"I'm out here because water harvesting turns even short rainstorms into long-lasting celebrations!"

PLAY TIME! I park my bike by the river to join kids jumping into cool, clear water. While swimming underwater, I find myself surrounded by frogs, salamanders, and fish—some bigger than my thigh! I even spot a family of beaver! I'm living within a nature documentary! I surface refreshed, to see diverse families picnicking, fishing, napping, and frolicking on the banks.

On shore again, I stroll by a photographic mural of the river's history illustrating just how dead, depleted, and polluted this river was until watershed-wide efforts—including those I walked and cycled by today—revived it. Former disastrous river-side flooding has been abated by removing constrictive buildings and pavement to reconnect the river and its tributaries to their broad floodplains. The reintroduced

beaver and their low, porous dams mellow storm and drought pulses in the river's flow and help ensure flow throughout the dry season. Stormwater is now cleansed and infiltrated within water-harvesting, soil-building riverside parks, perennially vegetated polyculture farms and pastures, and wilderness preserves that absorb flood flows like a sponge. The results are rebounding groundwater levels, bubbling springs, and sustained river flows.

I learn that the community's pulse is regularly taken and reported on by local media, including its air and water quality, river flow, groundwater levels, vegetative cover, soil organic matter and fertility, the vitality of populations of threatened and endangered species and their habitat, and the health and happiness of its citizens. The beneficial actions and innovations of individuals, neighborhoods, organizations, schools, government departments, farms, ranches, businesses, and industries are regularly spotlighted to show how they help improve the community watershed's health—and how others can do the same or better.

Contributing plants, animals, insects, and fungi are also celebrated. This week, native tortoises are highlighted for their habit of digging a basin when they sense rain so they can drink the captured storm-water, followed by the edible morning-dew-capturing wildflowers that proliferate around the basin after the tortoise moves on.

We should all have these experiences, everywhere, all the time. As individuals, communities, and societies, we should be surrounded by what we love, value, care for, and are inspired by, NOT by what we hate, fear, and are hurt by. To begin, we all know that clean, accessible water is essential to life and health, so let's enhance our water supply through individual and collaborative action, everywhere, all the time. Then our actions will grow until we are indeed surrounded by what we love, value, care for, and what truly sustains us.

Every aspect of the world we design and build should filter, diversify, and share the rain—along with all other water supplies—so that water quality, quantity, availability, and accessibility steadily improve for everyone. We can make this ever-cleaner water available for an ever-greater array of uses, lives, and interactions. As you've seen in this book, there are myriad ways to do this simply by collaborating with our local ecosystem rather than relying on purchased products. The choices we make about how we build, feed, transport, produce, power, educate, and recreate, should clean and enliven water—along with the air above and the earth

below—because together these are our sources of rain, surface water, groundwater, food, wildlife, and a life-sustaining climate.

Start here, start now.

Plant the rain! Grow abundance!

Appendix 1
Water Levels, A-Frame Levels, and Laser Levels

TOOLS FOR MEASURING SLOPE, ELEVATION RELATIONSHIPS, AND DETERMINING THE PLACEMENT OF WATER-HARVESTING EARTHWORKS AND ASSOCIATED PLUMBING

Professionals typically use a laser level or transit/surveyor's level to measure slope, elevations, and/or define how they want to shape the land. These tools work well, but they are expensive. So we begin with two effective and inexpensive alternatives you can make—a "*bunyip*" *water level* and an *A-frame level*.

THE "BUNYIP" WATER LEVEL

The "bunyip" (fig. A1.1), as this water level is called in Australia, is a simple tool that enables you to find a land "contour" (a level line on the landscape), determine elevation differences between two points, and determine the slope of the land.

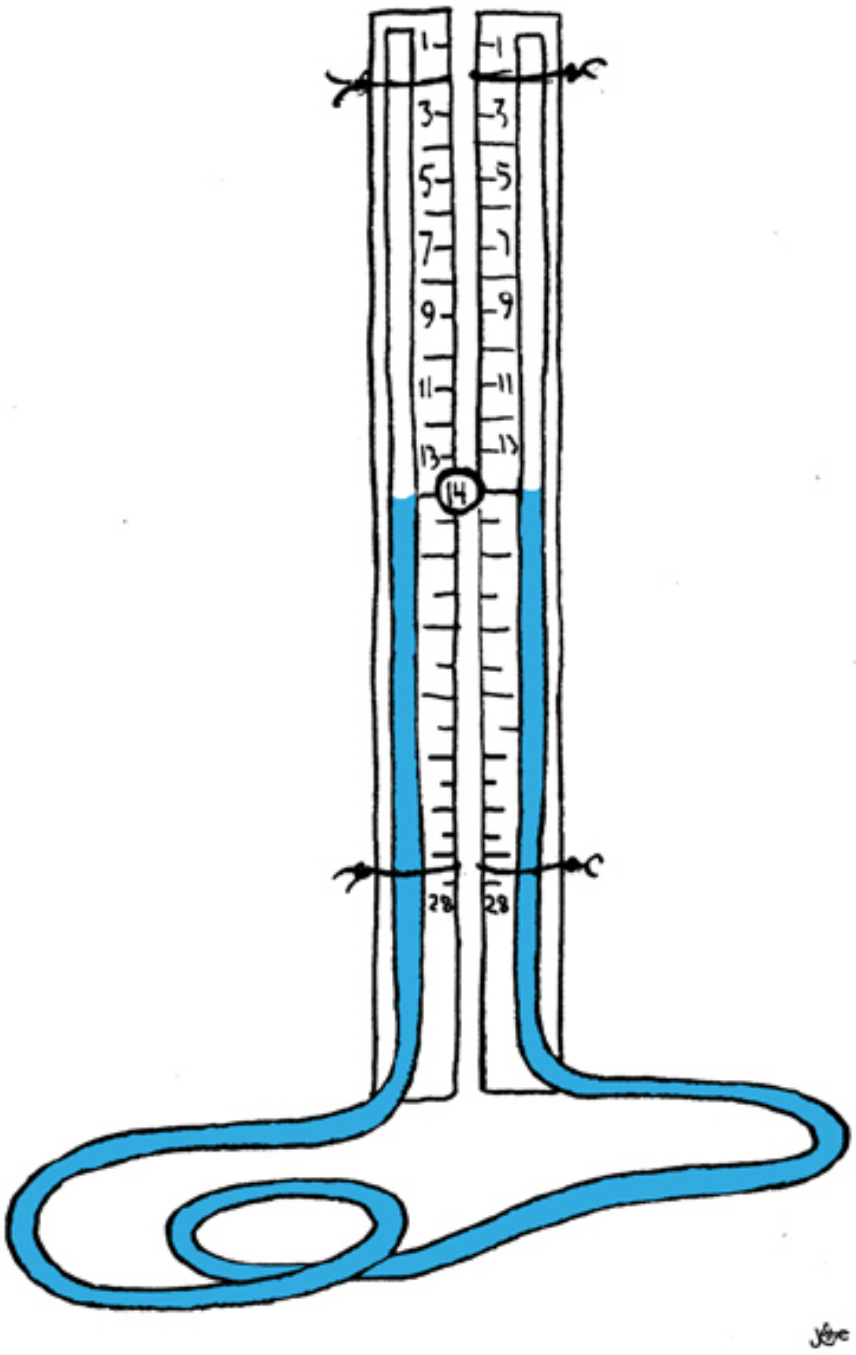


Fig. A1.1. Bunyip water level

You can use this tool to mark the locations for contour berms, slopes of diversion swales, end points of boomerang berms, depths of basins, and appropriate locations for overflow routes. In addition, you can determine how much a gravity-

fed greywater pipe will need to drop in elevation as it maintains a minimum 2% slope from where it exits a house to the point it outlets into the landscape.

A bunyip consists of a long clear vinyl tube, with each end attached to a tall stake that is marked in inches or centimeters. When the two stakes stand vertically, the tube becomes "U" shaped. Water is then poured into the tube, and air bubbles and kinks are removed so the water flows freely within (box A1.1). The bunyip works on the principle that still, standing water is level across its entire surface, as you would find on a calm lake. A bunyip is basically a lake in a tube.

Box A1.1. Getting Rid of Air Bubbles in Bunyip Tubing

To ensure accurate water level measurements, enlist a friend to help you remove air bubbles in tubing. First, pour water into bunyip tubing. Next have your friend hold the two bunyip stakes upright next to each other. Then stretch the intervening tubing out along the ground. Where the tubing "folds" back on itself (the bottom of the "U"), pick up both parts of the tubing 2 feet (0.6 m) from the bottom of the "U," using one hand. Make sure the tubing is not pinched anywhere. The bottom of the "U" will hang down forcing any air bubbles in that length of tubing to rise toward your raised hand. Now slowly slide your hand up the tubing, always keeping the bubble-free section of tubing lower than the tubing in your hand. Tap the tubing with your free hand to help free any bubbles sticking to the side. When your hand gets to the stakes, drop your hand slightly or lift the stakes slightly so the collected air bubbles can escape out the open ends of the tubing (fig. A1.3).

You may need to add more water in the tubing to fill the space the bubbles occupied. After you've put more water in, check for bubbles again.

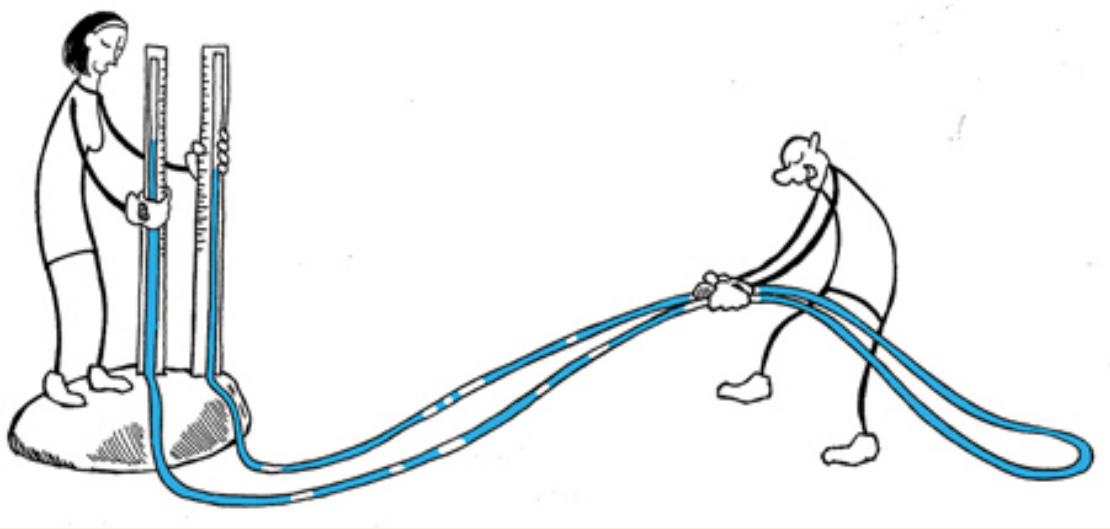


Fig. A1.3. Removing air bubbles from tubing

The tube is filled with enough water so the surface of the water reaches about halfway up each vertically held stake. If the stakes are standing right next to each

other on level ground, the water level will be the same in both ends of the tube, and the measurement reading on each stake will be the same. If one stake is raised while the other stays where it was, the water level will stay straight across, but the measurement readings on the stakes will be different, reflecting the elevation difference of the bottom of the stakes. It takes two people to use a bunyip water level—one to hold each stake. Bunyips are easy to make using the materials and instructions below.

WHAT YOU NEED TO MAKE A BUNYIP

- Two 5- to 6-foot (1.5- to 1.8-m)-tall, straight stakes (2 x 2s work well)
- 30 feet (10m) or more of 3/8-inch (10-mm) interior diameter thin-walled clear vinyl tubing (thick-walled tubing kinks more and is a waste of material), availab in the plumbing section of most hardware stores
- 3 feet (90 cm) of wire, string, or duct tape to bind the tubing to the stakes
- Yard (meter) stick or tape measure
- Permanent ink marker
- 2 to 3 gallons (9 liters) of water
- Funnel to pour water into the tubing

• Optional: 2 corks and 2 strings. Corks are used to plug the tube ends when moving the water level around, then removed during use. Wine bottle corks can be whittled down to fit the tubing. Tie one end of a string to the top of the bunyip stake and the other end to a cork so you don't lose the corks.

HOW YOU MAKE A BUNYIP

Lay the stakes beside one another on the ground with the bottom ends even. Measure 5 feet (1.5 m) up from the bottom of each stake and mark this point. These marks should be level with one another since the bottom ends of the stakes are even. Starting from the upper mark of each stake, use the measuring tape or yard stick and permanent marker to mark each inch (or centimeter) going down for 30 inches (or 75 cm). Check the accuracy of the marks by standing the stakes next to each other on level ground to confirm they line up. Starting with zero at the top, number the marks from top to bottom on each stake so the numbers also correspond.

Bind the tubing near the top of each stake using wire or string. Lash it tight enough to hold the tubing in place, but not so tight that it significantly pinches

the tubing. Pull the tubing straight down along the stake and lash it in the middle, then near the bottom of the stake.

Fill the tubes with water in one of two ways:

Method 1: *Pour the water in*. With both stakes in an upright position, carefully pour water into one end of the tube until water overflows the tube. Any air bubbles that become entrained in the tubing will prevent accurate water level measurements. Remove air bubbles from the tube (see box A1.1 for instructions), and add more water until the desired water level is attained.

Method 2: *Siphon the water in*. Lay one stake on the ground. Set the other stake upright against a table that has a bucket of water standing on it. Release the upper tubing from the upright stake and stick the end of the tubing in the bucket of water. Wash the end of the tubing of the stake laying on the ground, then suck on the end of the tubing to initiate water siphoning. Air bubbles typically do not get entrained in siphoned water running from the bucket into the tubing.

With the air bubbles removed, hold the stakes upright next to one another on level ground. Check that the level of water is about halfway up the stakes. Drain or add water as needed to get water to the right level. Water should move freely up and down in the tubing when you move the stakes. If water does not move, check the tubing for kinks, remove the kinks, and verify that water moves correctly. Once the water becomes calm after moving the tubes, check that the water level lines up in both tubes, and that the measurement reading is the same on both stakes. If the water levels are not at the same height when the stakes are standing next to each other on level ground, check again for air bubbles or a kink in the tubing. If the measurement reading is not the same, check for mismarked stakes.

Now your bunyip is ready to use. While carrying it around, use the corks or your thumbs or fingers to plug the tubing to keep water from spouting out the ends. Remove corks or thumbs when you are reading water level measurements. During a long project, it's a good idea to periodically set stakes on level ground next to each other to verify no new bubbles or kinks have formed.

USING YOUR BUNYIP—TWO HYPOTHETICAL EXAMPLES

Marking a level line for a contour berm

Al and Bonnie want to mark a level contour line on their land where they plan to dig a contour berm later that day. They get out their bunyip water level and

Bonnie holds the two stakes upright as Al fills the tubing with water and gets rid of air bubbles. The water is about halfway up their stakes and is level, so they are ready to start.

To refamiliarize themselves with the water level, Bonnie holds one of the stakes a few inches (cms) higher than the other. When the water stops moving, the water in the higher stake reads “19” while the lower stake reads “11”, with both stakes vertical (figs. A1.2 and A1.4), so they are reminded that the stake that reads the higher number is also higher in the landscape than the other stake.

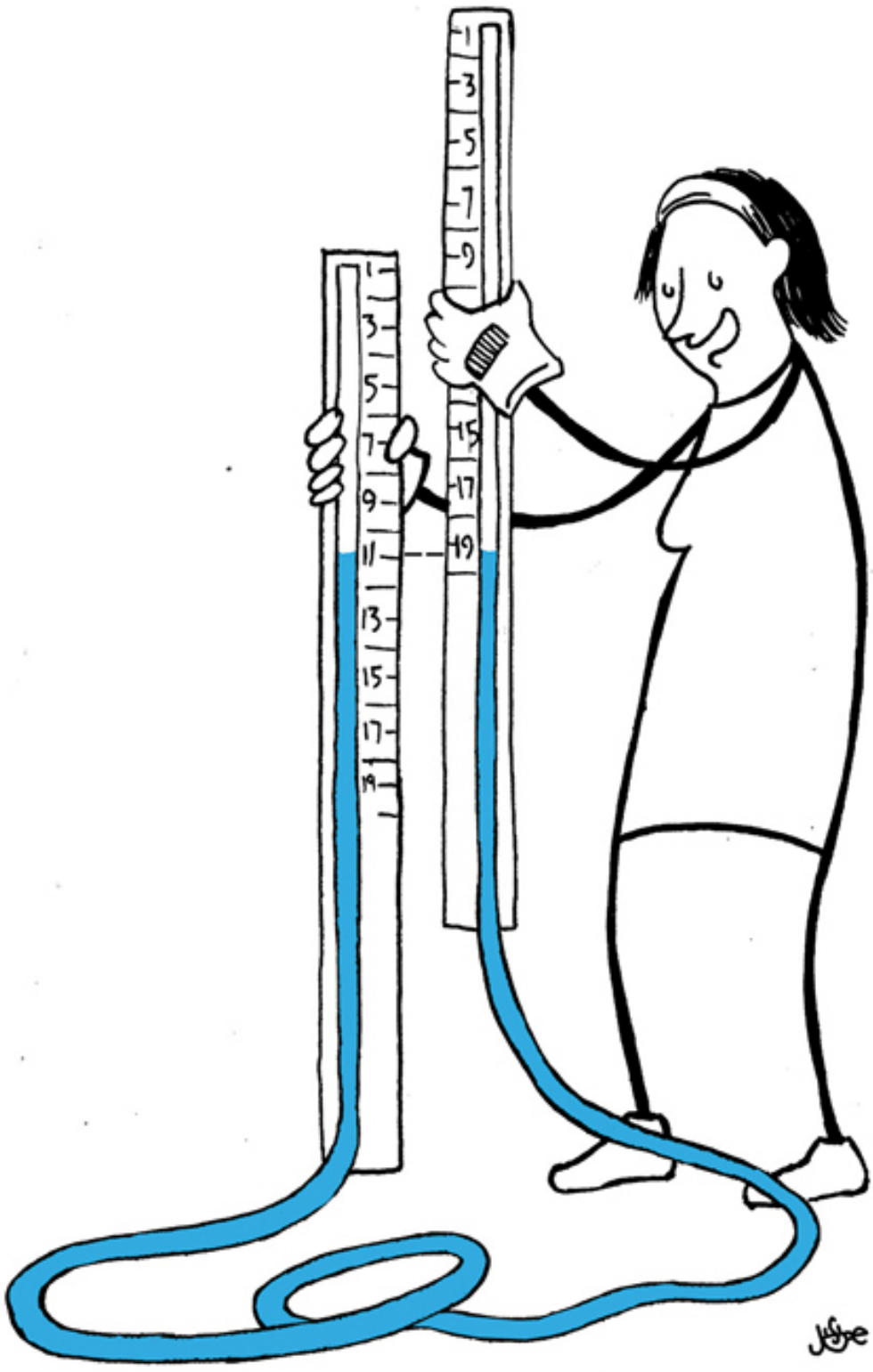


Fig. A1.2. Testing the bunyip level; the water is level.

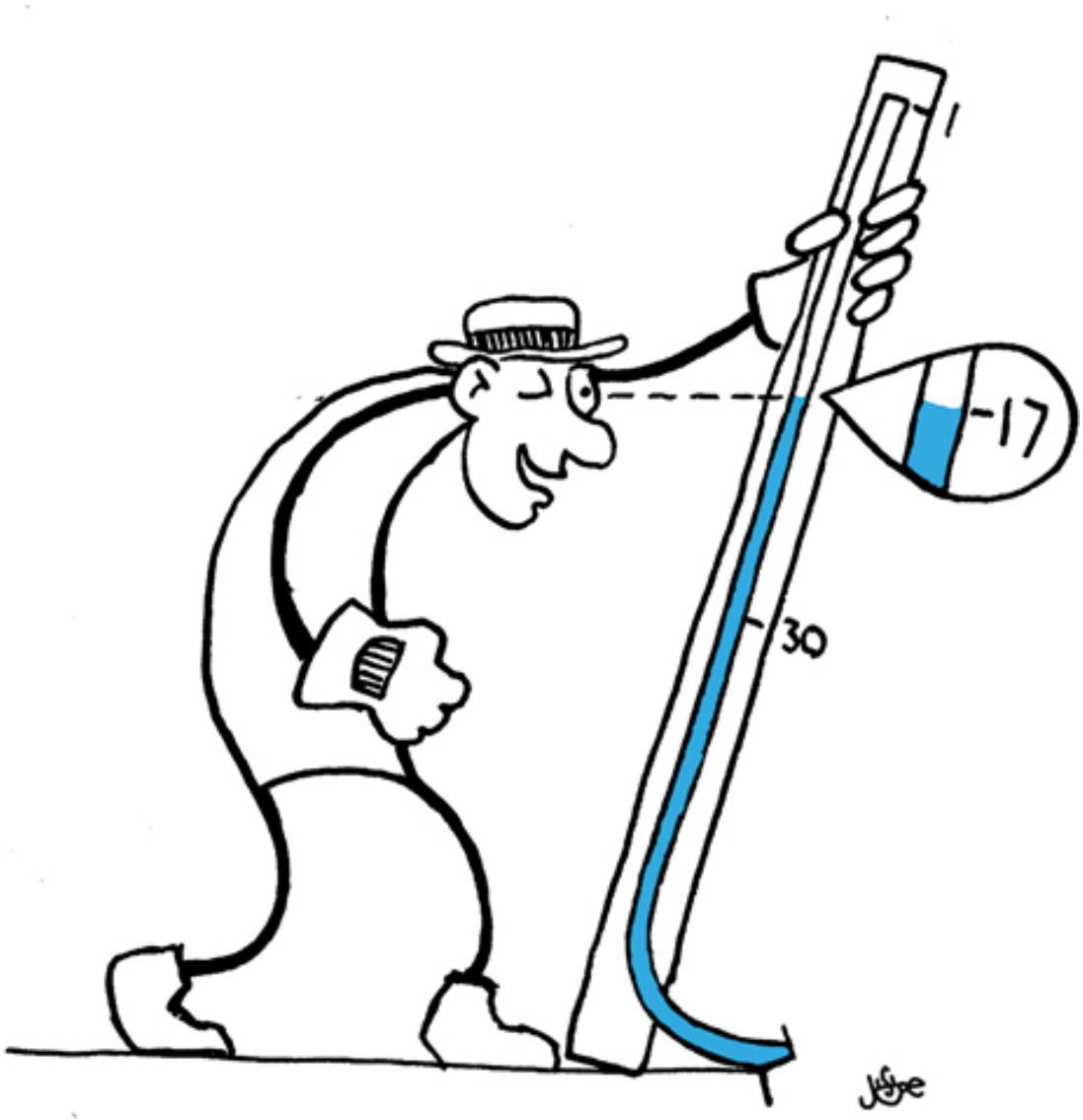


Fig. A1.4A. A non-vertical bunyip stake will give a lower, incorrect reading

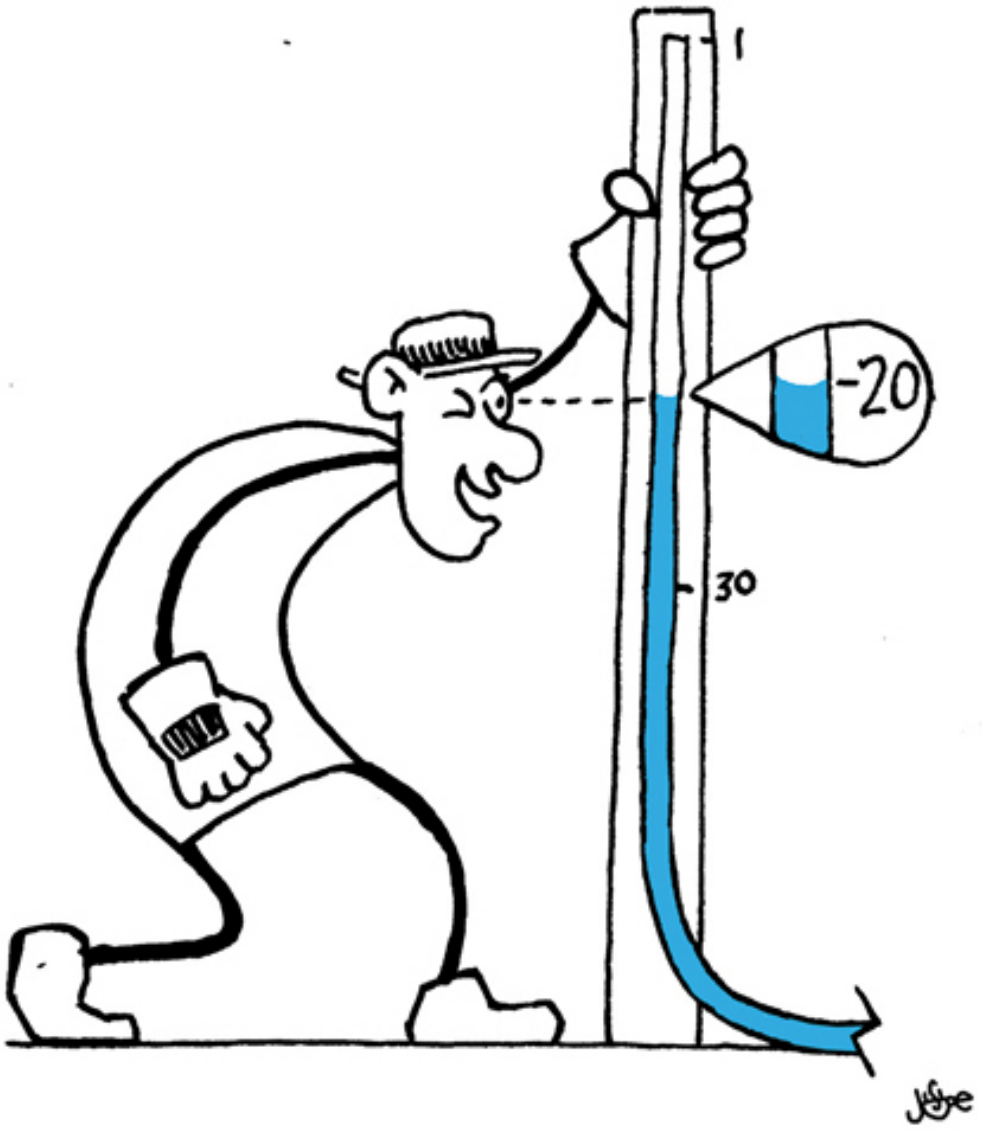


Fig. A1.4B. The bunyip stake must be vertical for a correct reading

As they walk to where they want to begin measuring the contour line, they each hold a stake with their thumb over the open end of the tube to keep water from spilling out. Bonnie sets the bottom end of her stake down where they want to begin the berm. Al walks 5 to 20 feet (1.5 m to 6 m) along what he thinks is the contour line (20 feet if the land is relatively flat, closer if the land is more undulating). Al puts his stake down in a spot he feels is on the same contour line as Bonnie's stake. Standing in these positions, they each gently tap the top of their end of the tube with their thumb to stop the water sloshing around within the tubing. When the water is still, and they've removed their thumbs from the end of

the tubing, they tell each other what water level measurement they have. Bonnie reads 13 while Al reads 17.

"I have the higher number, so my stake is higher than yours," says Al. "So I'll move my stake downslope a bit. You stay where you are since you're in the spot where we want to begin the berm." After moving his stake several times, Al and Bonnie each read 15 on their stakes, so they are now at the same elevation. They scuff a line in the dirt connecting Bonnie's point to Al's. With that done, Al keeps his stake in place and puts his thumb on the top of the tubing. Bonnie plugs her end of the tubing and walks her stake beyond Al ("leapfrogging him") to a point she thinks is level with his stake (fig. A1.5).

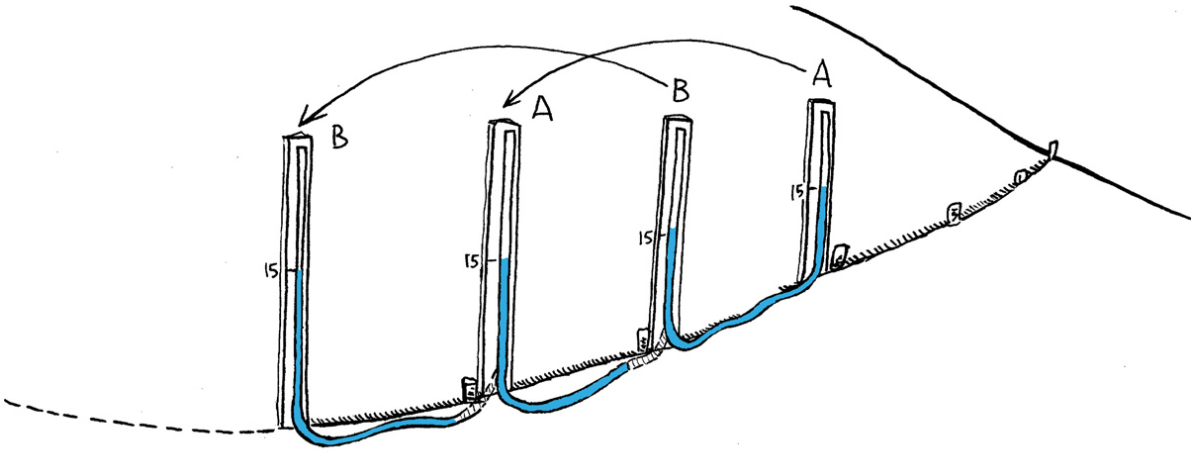


Fig. A1.5. Leapfrogging the bunyip to mark a level contour line on the land. Here the contour line is marked both by scuffing a line in the dirt and with stakes.

As Al and Bonnie find a series of points on the same land contour, they continue to connect the dots by scuffing the contour line into the dirt. They could have marked the contour line with wooden stakes or other markers, but since they planned to dig a berm 'n basin along the contour line right after lunch, scuffing is sufficient. They keep going until they reach the full length chosen for the contour berm. If they had encountered a landform that presented a natural barrier, they would have stopped there instead.

With the contour line marked, they prop the bunyip water level against a tree to keep water from running out of the tubing, call some friends, and dig a contour berm along the line they just marked (see chapter 2 on berm n' basins for more information about construction). By four o'clock that afternoon, the contour berm is complete.

Using a bunyip to determine a difference in elevation and measure slope

In the middle of a record-breaking drought, friends of Bonnie and Al decide to make use of the rain that does eventually fall by putting in a water-harvesting basin in front of their house. To make sure they don't dig into and damage underground utility lines they call their free local utility-marking service (in many states, dial "811") to have buried lines marked between the public right-of-way and the meters. Then they hire a private utility-marking service to continue marking buried lines from the utility meters to the house. Once all utility lines are marked, they ask Bonnie and Al to bring their bunyip over and help them figure out the direction water naturally drains around their new home.

Bonnie and Al look at the relatively flat lot and try to eyeball the way water would flow, then get out their bunyip water level to see if they are right. "OK," says Bonnie, "I'm putting my stake by the house." Al places his stake 10 feet (3 m) away from the house at a point he thinks is directly downhill from Bonnie. When the water stops moving within the tubing, Al and Bonnie tell each other the water level readings they have (fig. A1.6A).

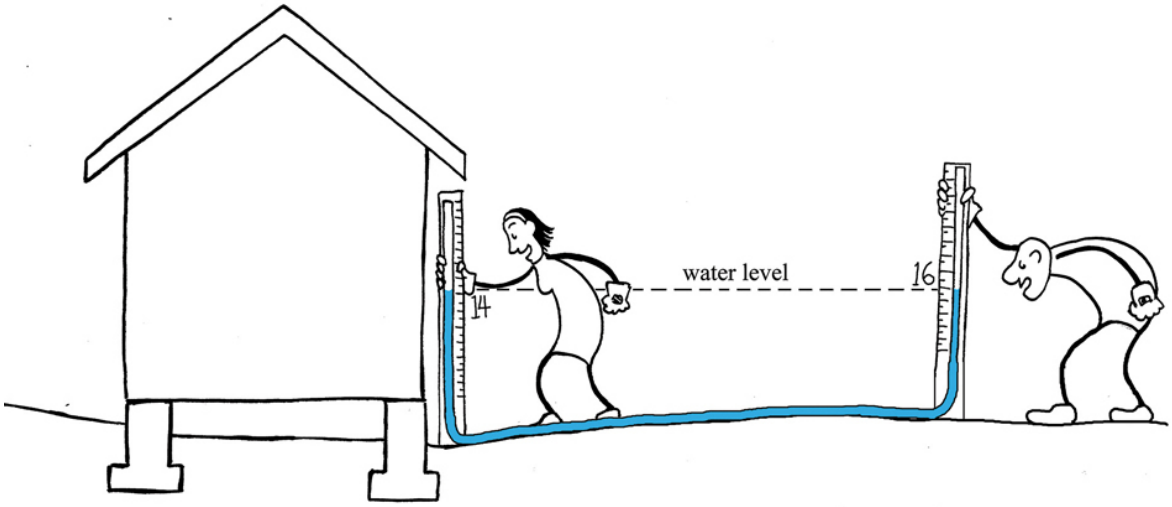


Fig. A1.6A. Bunyip shows land slopes toward house

"I've got 14," says Bonnie. "My stake reads 16," says Al, "and with our bunyip that means you are a full two inches lower than me, so water will drain toward this house…which is bad news!"

Al, Bonnie, and their friends decide to dig a shallow basin about 15 feet (4.5 m) from the house to intercept rainwater, and to move the soil from the basin to the

house foundation to deflect rainwater away from the house. They dig out a level-bottomed basin 6 feet (1.8 m) wide and 8 feet (2.4 m) long, and put most of the fill dirt next to the house, making sure the dirt is at least 4 inches (10 cm) below the top of the foundation's stem wall (as recommended by local building codes to keep termites and/or soil moisture from entering the home). They rake the area between the newly dug basin and the house so the grade slopes away from the house and into the basin. Then they use the bunyip water level to check their work. Bonnie again stands by the house and Al places his stake about halfway between the house and the basin on the new slope they created.

"My stake reads 16," announces Bonnie.

"And I read 14, so we did reverse the slope and water will now drain away from the house," cheers Al. "Bonnie, stay up against the house while I move my stake to the bottom of the basin to see how much deeper it is than the soil by the house."

Al moves to the bottom of the basin and reads 6 on his stake (fig. A1.6B).

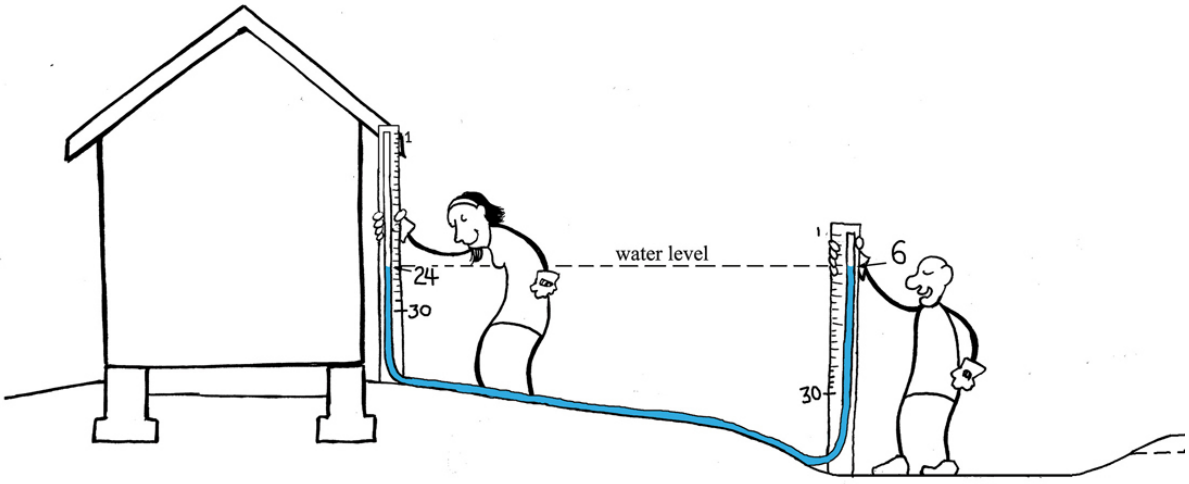


Fig. A1.6B. Using a bunyip to measure how much lower the bottom of the basin is than the area near the house, confirming that the slope now drains away from the house

"I've got 24" exclaims Bonnie. "Subtract your 6 from my 24 and that tells me you are 18 inches lower than me. We did a good bit of digging!"

"This basin will catch a lot of rainwater! Let's make sure when it fills up, any surplus water will overflow away from the house," says Al.

They take land-surface readings all around the edge of the basin using their bunyip water level. They learn from the readings that if water flows out the lowest point around the edge of the basin, it will drain water toward the neighbor's

house. To change this, they pick up the shovels and alter the dirt level of the basin's rim slightly so the lowest point on the basin's edge will now direct overflow into another basin on site.

Checking their work with the bunyip as they go along, they dig several more basins, this time located in the public right-of-way (public land located between their property line and the street). These basins will harvest even more rainwater and will receive overflow from the basin they dug in front of the house. So this series of basins will direct overflow water all the way from the house to the street. The edges, bottoms, and general slope of the basins are checked using the bunyip one last time.

The basins were constructed so that while the overflow spillways that move water from one basin to the next are at the same elevation, that elevation is well below the soil level abutting the house. This way the house will stay high and dry. The elevations of the level bottoms of the basins varied, but were all lower than their respective overflow spillways, so some water will be retained in each basin. The depth between a basin's overflow spillway and the bottom of the basin determines the storage capacity of the basin.

Bonnie and Al's friends are delighted with their new water-harvesting basins. After taking a break, they plant the basins. Hardy native trees go in along the street in the public right-of-way basins. The basin in front of the house is planted with a drylands-adapted peach tree to provide fruit for future pies. Along with it, they plant a wolfberry, a chuparosa, and native flowers that produce native foods and medicinals and attract hummingbirds. This basin will receive direct rainfall, harvested runoff, and greywater from the home.

Bonnie and Al's friends are so inspired, a week later they dig several more basins near their house. A vegetable garden goes into the basin on the equator-facing side of the house where it will receive winter sunlight. A native mesquite tree is planted in a basin west of the house to fix nitrogen in the soil and screen the vegetable garden from harsh summer-afternoon sun. Once all the basins are dug, planted, and well-mulched, Bonnie and Al's friends dance together to entice the rain (fig. A1.6C).

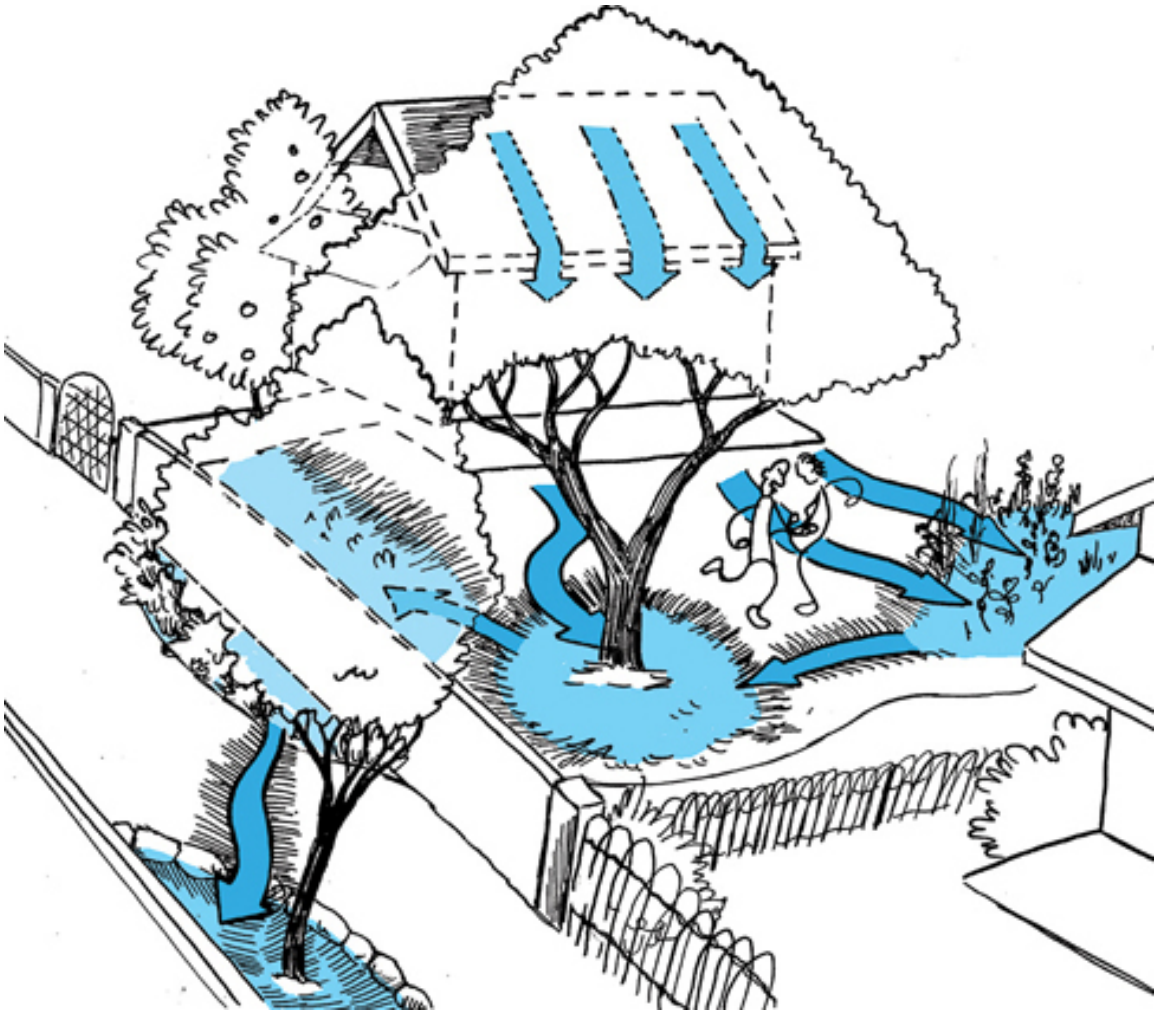


Fig. A1.6C. Celebrating completion of a water harvesting landscape

For more information see chapter 2 on infiltration basins, chapter 11 on vegetation, chapter 4 in Volume 1 on integrated design, and the video page at HarvestingRainwater.com.

THE A-FRAME LEVEL

The A-frame level (fig. A1.7) is even simpler to construct than the bunyip water level. No tubing or water is needed, and you can use it all by yourself. An A-frame level can be used to find a contour line on the landscape, but unlike the bunyip, you cannot measure the elevation differences between two points at different levels, nor can you measure the slope of the land. It does come in very handy for marking the line on which to construct contour berms and for checking to see if the two ends of a boomerang berm are level.

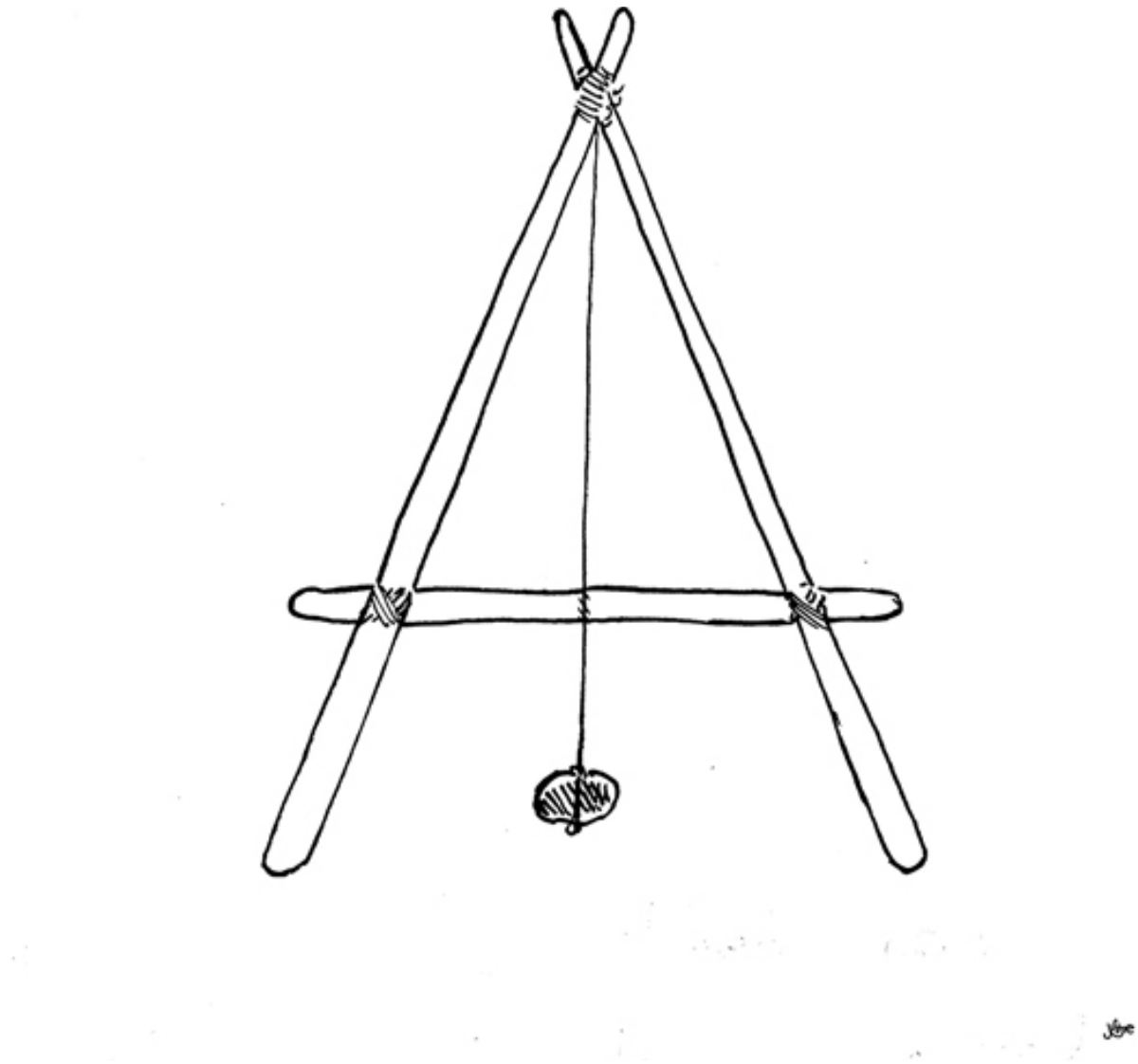


Fig. A1.7. A-frame level

The A-frame level is made of three poles or sticks tied or fastened together to form a capital "A" (thus the name). A weighted string is hung from the top of the "A" like a plumb bob. When both "feet" of the "A" are level with one another the weighted string will hang alongside a center line marked on the horizontal stick of the A-frame. If the two feet are not level with one another, the string will hang to one side or the other of the center mark, depending on which foot of the A-frame is lower.

WHAT YOU NEED TO MAKE AN A-FRAME LEVEL

- 3 straight poles, pipes, sticks, or something similar. They must be long enough s that the top of the "A" is about as tall as you are and the feet of the "A" are at le 3 feet (0.9 m) apart. The feet can be closer together, but the narrower the "A" th longer it will take to mark a level contour line on a slope.

- Rope, cordage, nails, or screws to securely fasten the poles, pipes or sticks togetl at 3 points

- A piece of string about 4 feet (1.2 m) long and a weight of some sort (stone, horseshoe, etc.) to tie to one end of the string

- Marker, knife, or paint

HOW YOU MAKE AN A-FRAME LEVEL

Lay your three stakes, poles, or sticks on the ground in the form of a capital "A." Tie or screw the three stakes together in the three points where they touch. This is a great opportunity to live out your Boy Scout or Girl Scout knot-tying fantasies with clove hitches and lashing! Make sure all bindings are tight so that your A-frame level won't come apart and the joints don't loosen, as that would result in inaccurate readings.

Once bound, set the A-frame upright and tie one end of the string to the top of the "A." Tie the weight to the other end of the string. The heavier the weight, the less likely it will get blown around on a windy day. The weighted end of the string should hang below the cross stake (the stake parallel with the ground). To make the center mark on the cross stake, place the feet of the upright A-frame on a section of unlevel ground, so one foot of the A-frame is a little higher than the other. When the weighted string comes to rest in a spot alongside the cross stake of the A-frame, lightly mark that spot (fig. A1.8A).

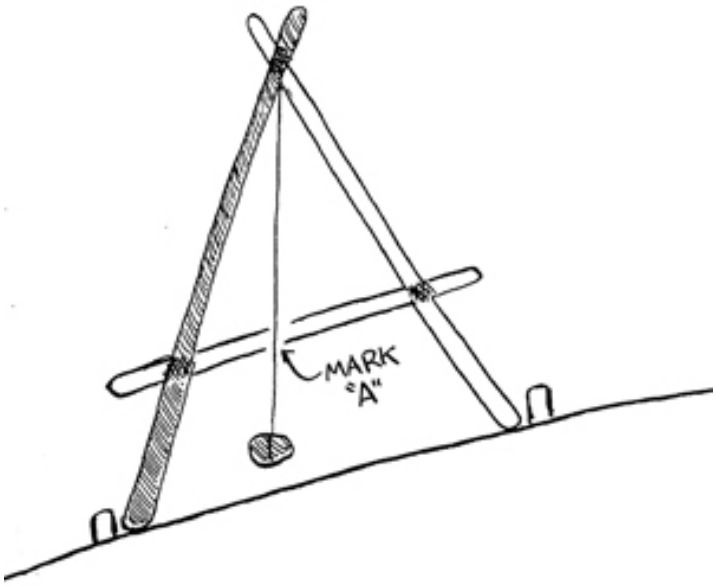


Fig. A1.8A. Calibrating the A-frame, step one

Now, mark the two points where the A-frame is standing on the ground. Lift the A-frame, rotate it, then set it back down with the "feet" switching places. When the weighted string again comes to rest alongside the cross stake, lightly mark that spot (fig. A1.8B).

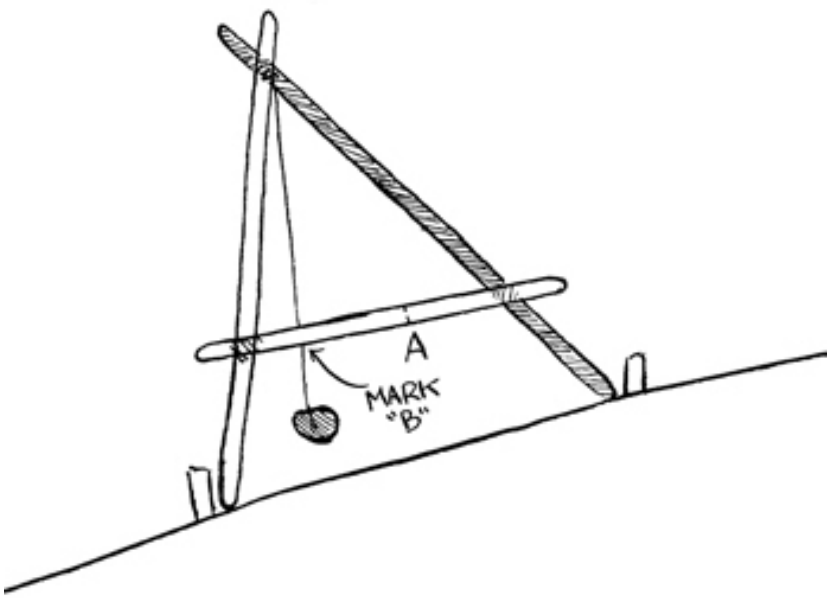


Fig. A1.8B. Calibrating the A-frame, step two

Now you have two marked spots on the cross stake. Permanently mark the midpoint between these two spots on the cross stake (fig A1.8C).

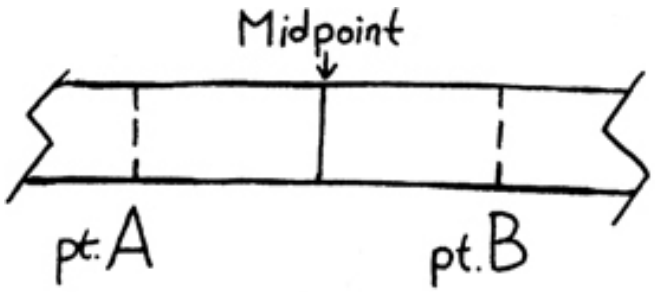


Fig. A1.8C. Calibrating the A-frame, final step

From now on when the weighted string comes to rest alongside this permanent mark, you will know the two feet of the A-frame are standing on two points level with one another.

Your A-frame will read accurately as long as it does not loosen up and change shape. You can quickly test it by going through the steps just described. If the heavy mark is still at the midpoint when you test it on level ground, then your A-

frame will read correctly. If the mark is not at the midpoint, retighten the joints and make a new midpoint mark.

HOW TO USE AN A-FRAME LEVEL

Go to a spot where you want to mark a level contour line across the landscape. Place the A-frame upright with its "feet" on what you think is level ground, and see where the weighted string comes to rest along the cross bar. If the string comes to rest alongside the permanent mark, the feet of the A-frame are on a level line. Now mark a straight line in the dirt from one foot of the A-frame to the other. Rotate the A-frame 180° with one foot left standing on the end of the line you just marked and the other foot moved to a new spot you think will be level with the first (fig. A1.9). If the weighted string comes to rest to either side of the permanent mark, the A-frame is not on a level line. Move the newly placed foot slightly up or down the slope until it rests on a spot that is level with the other foot. Again, mark this straight line in the dirt. Continue finding and marking the level contour line by rotating and stepping the A-frame across the landscape. Repeat this process until you have marked the contour line length needed for your project.

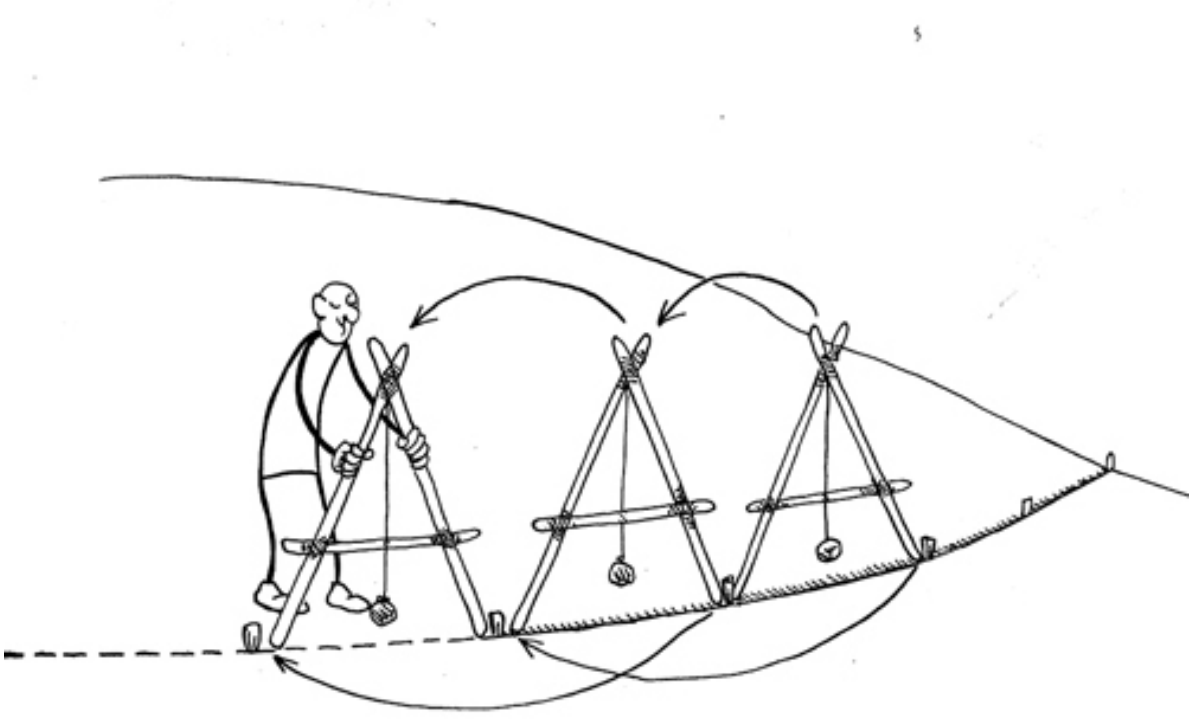


Fig. A1.9. Using an A-frame level, finding and marking a level contour line

Once finished, the marked contour line may be rather zig-zaggy, but you can smooth out the line within the zig zags to a more curvilinear shape when you plant the contour line or construct a structure such as a berm 'n basin or sheet flow spreader atop it. Just make sure the top of the structure remains level.

AN A-FRAME VARIATION FOR WINDY SITES

On very windy days the weighted string of the A-frame will blow around. A variation used by Chris Meuli on his windblown New Mexico land was built by lashing a line-level tool to the horizontal cross stake instead of using a weighted string (fig. A1.10). If you construct this type of A-frame, you'll need a line level, a *straight* cross stake, and a level place to build the device. With both feet of the "A" on level ground, secure the cross brace so the line level's bubble is right in the middle of the cross brace reading "level."

Fig. A1.10. Chris Meuli's line-level A-frame. A bubble level tool is lashed to horizontal bar (look below Chris' toes). Chris bolts his A-frame together with wing nuts so he can disassemble and fold it up for easy storage. His A-frame is only as tall as his waist, which allows him to use the tool under the branches of trees.

LASER LEVELS

One person can operate a rotating laser level. This device consists of a self-leveling, rotating laser-beam transmitter attached to the top of a tripod plus a separate elevation measuring rod with a laser receiver/reader bracketed onto it. A

laser level is very accurate and easy to use, but it is the most expensive tool presented in this appendix.

Ideally you keep the laser level's transmitter (and the tripod it sits upon) in one position while taking all your measurements, because the laser's elevation will be your reference elevation (at different locations you'll be measuring the vertical distance between a point in the landscape and the laser). The laser transmitter projects a laser beam in a full 360° circle, so position it atop the tripod in sight of all the locations you want to measure, making sure no trees, buildings, or other objects will obstruct the laser beam.

When you position the laser transmitter, adjust the tripod's legs so the top of the tripod is close to level. Next, turn on the laser and wait for the transmitter to make the needed final adjustments to become truly level. If the transmitter makes a warning sound, the tripod position is too far out of level for self-adjustment. In that case, turn off the level before the transmitter's motor burns out, readjust the tripod to get it closer to level, and try again.

With the laser turned on and spinning, turn on the laser receiver/reader, attach it to adjustable measuring rod, place the rod where you want an elevation measurement, then slide the receiver up or down the rod until the laser receiver starts to beep. An arrow on the laser receiver points up if you need to move the receiver up to find level, or points down if you need to move the receiver down (fig. A1.12). The closer the receiver is to the same elevation as the laser transmitter, the more quickly it will beep. When intermittent beeps become a single continuous sound, the laser receiver is level with the laser and a flat bar appears on the display.

Fig. A1.12. The arrow on the laser receiver's display signifies that the receiver must be moved down to become level with the laser transmitter. As needed, you can slide the receiver itself up or down on the measuring rod, or slide the adjustable section of the measuring rod up or down; or move the base of the measuring rod to a higher or lower point in the landscape if you are trying to find a point that is level with a section of the landscape previously measured.

Do not look directly at the laser—it can hurt your eyes.

Note that most laser levels have the number "1" located at the bottom of the measuring rod—this is the opposite of most bunyip water level's elevation rods, which have the highest number located at the bottom. So when you take elevation readings at different locations using a typical laser level, the higher the number, the lower that location is in the landscape. This is not intuitive to me, so when I use a laser level, I constantly remind myself that *the higher the number the lower the elevation, and the lower the number the higher the elevation*.

Take measurements throughout the planning, placement, and building of an earthwork. One person can do this—though it can be helpful if one person holds

the rod and reads the laser receiver, while another writes down measurements at different points in the landscape.

In fig. A1.11A-D and A1.13, laser level measurements were taken after construction to determine how well this earthwork basin was built by others.

Fig. A1.11A. Omar is using a laser level to take an elevation measurement at the curb cut inlet of a street-side rain garden's water-harvesting basin. This is the reference elevation: we want to know how much higher or lower all other points are in relationship to this point where water will enter the basin.

Fig. A1.11B. Next, Omar is taking an elevation measurement at the bottom of the infiltration basin. The deeper the basin bottom is in relation to the curb cut inlet, the greater the basin's water-harvesting capacity. If the basin bottom is higher than the inlet, it won't work.
In this case, the basin bottom measured *beneath the mulch* was 8 inches (20 cm) deeper than the inlet. This will work, but it's not ideal. I prefer a depth of at least 12 inches (30 cm) measured beneath the mulch, and a minimum 8 inch (20 cm) depth if it's measured from the *top of the mulch*.

See chapter 7 for how a *vertical mulching* strategy could be used to increase the water-harvesting capacity of this basin.

Fig. A1.11C. Omar is taking an elevation measurement on the planting terrace of the rain garden's infiltration basin. Ideally, the top of the terrace is built *no higher* than the elevation of the curb cut inlet so storm-captured runoff will rise to the top of the terrace, saturating it and the plants' root zone.

Fig. A1.11D. Omar is measuring the elevation of the rain garden's top zone on its downstream side. Ideally, this point should be at least 4 inches (10 cm) higher than the curb cut inlet of the *eddy basin* shown here (or the curb cut outlet of a *flow through basin*) to ensure that water will not overflow and erode the dirt pathway. In this case, the top of the rain garden's downstream side is 7 inches (18 cm) higher than the curb cut inlet, so all is good. Note, for easier pedestrian access, the top of the dirt path should not be higher than the sidewalk elevation, nor more than 2 inches higher than the top of the street curb. See chapter 8 and (5 cm) fig. 8.43 for more on *eddy* or *backwater* basins and important considerations for this elevation relationship.

A1.13. This much less expensive laser level only points in one direction at a time. Check bubble in level's vial to make sure it is level, then observe the elevation differences of various points to the elevation of the laser. Here Omar is checking elevation of a planting terrace in relation to the basin's curb cut inlet.

In this case, the terrace was found to be 2 inches (5 cm) higher than the curb cut inlet. Not ideal because in small storms water flowing along the street curb will be just 1 to 2 inches (2.5 to 5 cm) deep, and will be unlikely to rise to the level of the terrace and its plantings. But the terrace can work in a big storm when flow will be deeper—typically 4 inches (10 cm).

To give me a quick visual reference when I build such a basin, I find and mark a spot on the basin bank for the planting terrace that is no higher than the curb cut inlet (to maximize water capacity). I then shape the basin's dirt banks into the terrace at desired elevation, and check levels again. When all is correct I can then do the rockwork.

See chapter 11 for more on a rain garden's three planting zones—bottom, terrace, and top.

TOOL BOX LEVEL

Gravity-fed plumbing should be constructed and maintained with a minimum slope of 2% (1/4-inch drop per linear foot or 2-cm drop per linear meter). My favorite tool for measuring pipe slope is a 12-inch Empire Magnetic Tool Box Level, with Vari-Pitch vials that read slope in 1/8th-inch increments (figs. A1.14A, B, C).

Fig. A1.14A. 12-inch Empire Magnetic Tool Box Level positioned with magnet side up and grooved side down to fit on the pipe, so slope measurements can be read from the side of the level. See fig. A1.14B for close up.

Fig. A1.14B. Close up of level reading drop/slope of 1/4-inch drop per linear foot. Note how the right edge of the bubble on right vial touches and reads 1/4-inch slope.

Fig. A1.14C. Tool Box Level with its grooved side up and its magnetic side down. Vari-Pitch vial has been turned so slope measurements can be read from above. Here it reads level. Note how the edge of the bubble in the vial touches and reads "0."

The level's vials can be turned to change the direction from which their markings —and the slope of what the level is measuring—can be read. The body of the level has a grooved side that fits snuggly along a pipe, and a magnetic side that can conveniently adhere to metal pipe or gutters.

For additional photos and info check out the "Greywater Harvesting" page at HarvestingRainwater.com and its subpages "How to Get Slope Right on Gravity-Fed Greywater Distribution Plumbing" and "Greywater-Plumbing Options and Tips."

Appendix 2
Water-Harvesting Earthworks Calculations

List of Equations and Other Information

Box A2.1. Abbreviations, Conversions, and Constants for English and Metric Measurement Units

Equation 1. Catchment Area of Rectangular Surface

Equation 2. Catchment Area of Triangular Surface

Equation 3. Catchment Area of Circular Surface

Equation 4. Potential Volume of Rainfall On, or Runoff From, a Roof or Other Impervious Catchment Area

Box A2.2. Estimating Maximum Rainfall Runoff Using Rules of Thumb

Box A2.3. Meteorological and Climate Resources

Equation 5. Estimated Net Runoff from a Catchment Surface Adjusted by its Runoff Coefficient

Equation 6. Circular or Oval Infiltration Basin Water-Holding Capacity or Volume of Soil Excavated from the Basin

Equation 7. Square or Rectangular Infiltration Basin Water-Holding Capacity or Volume of Soil Excavated from Basin

Equation 8. Estimate Infiltration Basin (or other earthwork's) Minimum Annual Water-Harvesting Volume or Capacity

Equation 9. Estimate of Infiltration Basin Cost per Annual Water-Holding Volume or Capacity

Equation 10. Berm 'n Basin Water-Holding Capacity

Equation 11. Berm' n Basin Capacity per Unit of Length

Equation 12. Berm 'n Basin Spacing Distance

Equation 13. Terrace Capacity

Equation 14. Terrace Capacity per Unit of Length

Equation 15. Terrace Spacing

Equation 16. Optimum Terrace Width

Equation 17. Diversion-Swale Sizing

Equation 18. Calculating Rock Volume Needed for One-Rock High Structure

Box A2.1. Abbreviations, Conversions, and Constants for English and Metric Measurement Units

Note: * items are approximate

ABBREVIATIONS FOR EQUATIONS

sqrt = square root, which is a function on most calculators

ABBREVIATIONS FOR ENGLISH UNITS

inches = in
feet = ft
square feet = ft^2
cubic feet = ft^3
gallons = gal
acre = a
Fahrenheit = F

CONVERSIONS FOR ENGLISH UNITS

To convert cubic feet to gallons, multiply cubic feet by 7.48 gal/ft^3
* To convert inches to feet, divide inches by 12 in/ft
1 cubic yard = 27 cubic feet
1 ton = 2000 pounds
1 acre = 43,560 square feet
1 square mile = 27,878,400 square feet

CONSTANTS

Ratio between a circle's diameter and its circumference is expressed as = 3.14 *

ABBREVIATIONS FOR METRIC UNITS

millimeters = mm
centimeters = cm
meters = m
liters = l

kilogram = kg
hectare = ha
Celsius = C

CONVERSIONS FOR METRIC UNITS

To convert cubic centimeters to liters, divide cubic centimeters by 1,000
To convert kilograms to metric ton, divide by 1,000
1 metric ton = 1000 kg

CONVERTING BETWEEN ENGLISH UNITS AND METRIC UNITS

To convert inches to millimeters, multiply inches by 25.4 mm/in
To convert inches to centimeters, multiply inches by 2.54 cm/in
To convert feet to meters, multiply feet by 0.30 m/ft *
To convert square feet to square meters, multiply square feet by 0.092 m^2/ft^2 *
To convert cubic feet to cubic meters, multiply cubic feet by 0.028 m^3/ft^3 *
To convert gallons to liters, multiply gallons by 3.79 liter/gal *
To convert acres to hectares, multiply acres by 0.404 a/ha *
To convert miles to kilometers, multiply miles by 1.6 km/mi *
To convert Fahrenheit (F) to Celsius (C) for actual indoor/outdoor temperature measure ("it's 70 degrees outside today"), subtract 32 from Fahrenheit temperature, multiply result by 5, then divide by 9.
To convert Fahrenheit (F) to Celsius (C) for temperature difference ("it's 20 degrees hotter today than yesterday"), multiply Fahrenheit by 5, then divide by 9.

Equation 1A.
Catchment Area of Rectangular Surface (English units)

length (ft) × width (ft) = catchment area (ft^2)

EXAMPLE:

A house measures 47 feet long by 27 feet wide at the drip line of the roof. Note that it does not matter whether the roof is flat or peaked: The roof dimensions at the drip line are the same. It is the "footprint" of the roof's drip line that matters.

47 ft × 27 ft = 1,269 ft^2

1,269 ft^2 = catchment area

If the roof consists of two or more rectangles, calculate the area for each rectangle and add together. Again, take the view of a falling raindrop, and look only at the "footprint" of the roof's drip line. Roof pitch cannot be seen from above and does not matter. With conical, octagonal, or other non-standard roof shapes, again calculate the area based on the drip line.

Equation 1B.
Catchment Area of Rectangular Surface (metric units)

length (m) × width (m) = catchment area (m^2)

EXAMPLE:

15 m × 9 m = 135 m^2

135 m^2 = catchment area

Again, all the considerations in Equation 1A will apply.

Equation 2A.
Catchment Area of Triangular Surface (right triangle)

Multiply the lengths of the two shorter sides of the triangle then divide by 2 = catchment area

EXAMPLE:

A triangular section of roof measures 9 feet by 12 feet by 15 feet. This is a right triangle, with the 90-degree angle between the 9-foot and 12-foot sides. Taking the measurements of the two shorter sides:

(9 ft × 12 ft) ÷ 2 = catchment area (ft^2)

108 ft^2 ÷ 2 = 54 ft^2

54 ft^2 = catchment area

Equation 2B.
Catchment Area of Triangular Surface (standard math formula)

Multiply the triangle's base times its height then divide by 2 = catchment area

where the base can be any side, and the height is measured perpendicularly from the base to the opposite vertex.

EXAMPLE:

You want to know the area of a triangular section of patio. The length of the section in front of you is 20 feet (triangle base) and you measure 4 feet perpendicularly to the opposite vertex of the triangle.

(20 ft × 4 ft) ÷ 2 = catchment area (ft^2)

80 ft^2 ÷ 2 = 40 ft^2

40 ft^2 = catchment area

Equation 2C.
Catchment Area of Triangular Surface (Heron's formula)

This formula, attributed to Heron of Alexandria (first century A.D.), involves no trigonometry. It needs only the square root (sqrt) function found on most electronic or computer calculators. It may be useful when dealing with non-right triangles where you can measure (or know) all sides of the triangle.

Step 1: Determine the lengths of the sides of the triangle. These are a, b, c.

Step 2: Calculate s.
$(a + b + c) \div 2 = s$

Step 3: Calculate S, using:
$s \times (s - a) \times (s - b) \times (s - c) = S$

Step 4: Calculate the catchment area, which is the square root of S.
sqrt S = catchment area

Equation 3.
Catchment Area of Circular Surface

$\pi \times r^2$ = catchment area

Note: r = radius of the circle. A circle's radius is half its diameter.

EXAMPLE:

A circular roof has a 25 foot diameter. Divide the diameter by 2 to get the radius of 12.5 feet.

$\pi \times (12.5 \text{ ft} \times 12.5 \text{ ft})$ = catchment area (ft^2)

$3.14 \times 156.25 \text{ ft}^2 = 490.6 \text{ ft}^2$

490.6 ft^2 = catchment area

Box A2.2. Estimating Maximum Rainfall Runoff Using Rules of Thumb

ROUGH RULE OF THUMB FOR CALCULATING MAXIMUM RAINFALL RUNOFF VOLUME ON A CATCHMENT SURFACE (ENGLISH UNITS):

You can collect 600 gallons of water per inch of rain falling on 1,000 square feet of catchment surface.

ON THE REALLY BIG SCALE:
You can collect 27,000 gallons of water per inch of rain falling on 1 acre of catchment surface.

RULE OF THUMB FOR CALCULATING MAXIMUM RAINFALL VOLUME ON A CATCHMENT SURFACE (METRIC UNITS):
You can collect 1,000 liters of water per each 10 millimeters of rain falling on 100 square meters of catchment surface.

ON THE REALLY BIG SCALE:
You can collect 100,000 liters of water per 10 millimeters of rain falling on one hectare of catchment surface.

Box A2.3. Meteorological and Climate Resources

ONLINE RESOURCES

The United States National Weather Service's website. https://weather.gov/. Locate the weather stations closest to your site and find out their elevations. Download data from those stations that are most like your site.

Arizona Meteorological Network. https://cals.arizona.edu/AZMET/ Evaporation rates, prevailing winds, soil temperatures, and minimum/maximum temperatures are listed for various sites. For other states contact your local agricultural extension service for similar meteorological networks.

MISCELLANEOUS

See the One-Page Place Assessments page at HarvestingRainwater.com for a distilled page of great info on sun, climate, wind, water, watergy, watersheds, totem species, and more for many locations around the globe—and how to create your own.

The U.S. National Forest Service for remote weather stations, though the data is not as comprehensive or as standard.

Local airports.

Rain gauge from a hardware or garden store with which to begin keeping precipitation records for your site.

Equation 4A.
Potential Volume of Runoff from a Roof or Other Impervious Catchment Area (English units)

$$\text{catchment area (ft}^2\text{)} \times \text{rainfall (ft)} \times 7.48\ \text{gal/ft}^3 = \text{maximum runoff (gal)}$$

Note: For a more realistic estimate, see Equation 5.

EXAMPLE CALCULATING ANNUAL RUNOFF:

Calculate the maximum volume of rain, in gallons, running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. (In the example below, the roof dimensions at the drip line are

included in the calculation; the catchment area is the same whether the roof is flat or peaked.) Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 = maximum runoff (gal)
(47 ft × 27 ft) × (10.5 in ÷ 12 in/ft) × 7.48 gal/ft^3 = maximum runoff (gal)
1,269 ft^2 × 0.875 ft × 7.48 gal/ft^3 = 8,306 gal

8,306 gal = maximum runoff

EXAMPLE CALCULATING RUNOFF FROM A SINGLE RAIN EVENT:

Calculate the maximum volume of rain, in gallons, running off the roof in a single rain event from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. It is not unusual for heavy storms in the example area to drop 2 inches of rain. To determine the runoff from such a rain event you will divide the 2 inches of rainfall by 12 inches of rainfall per foot to convert inches to feet for use in the equation. Since the roof is a rectangular area, use the following calculation for catchment area:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 = maximum runoff (gal)
(47 ft × 27 ft) × (2 in ÷ 12 in/ft) × 7.48 gal/ft^3 = maximum runoff (gal)
1,269 ft^2 × 0.167 ft × 7.48 gal/ft^3 = 1,585 gal

1,585 gal = maximum runoff

For another example, illustration, and more explanation see box 1.3

Equation 4B. Possible Volume of Runoff from a Roof or Other Impervious Catchment Area (metric units)

catchment area (m^2) × rainfall (mm) = maximum runoff (liters)

Calculations for annual rainfall, a rainy season, or an event would be similar to those for English units.

Equation 5A.
Estimated Net Runoff from a Catchment Surface Minus Potential Water Loss (English units)

catchment area (ft^2) × rainfall (ft) × 7.48 gal/ft × runoff coefficient = net runoff (gal)

Impervious catchment surfaces such as roofs or non-porous pavement can lose 5% to 20% of the rain falling on them due to evaporation, wind, overflow of gutters, leaks in downspouts, and minor infiltration into the catchment surface itself. The more porous or rough your roof surface, the more likely it will retain or absorb rainwater. On average, pitched metal roofs lose 5% of rainfall, allowing 95% to flow to the cistern. Concrete or asphalt roofs retain around 10%, while built-up tar and gravel roofs can retain 15% to 20%. (However, the percent of retention is a function of the size and intensity of the rain event so more porous roof surfaces could absorb up to 100% of small, light rain events.) To account for potential loss, determine the runoff coefficient that is appropriate for your area and impervious catchment surface (0.80 to 0.95).

EXAMPLE CALCULATING NET ANNUAL RUNOFF FROM A ROOF:

Calculate the net volume of rain, in gallons, running off the roof in an average year from a home that measures 47 feet long and 27 feet wide at the drip line of the roof. Rainfall in this location averages 10.5 inches per year, so you will divide this by 12 inches of rainfall per foot to convert inches to feet for use in the equation. (Note: You can use the same equation to calculate the runoff from a single storm, by simply using the rainfall from that storm instead of annual average rainfall in the equation.) Assume that the loss of water that occurs on the catchment surface is at the high end of the range so you get a conservative estimate of net runoff. This means you select a runoff coefficient of 80%, or 0.80. You might want a conservative estimate if planning water needs for landscaping, but you might want an unmodified estimate if trying to size a cistern. Since the roof is a rectangular area, use the following calculation for catchment area, LENGTH × WIDTH as in Equation 1A:

(length (ft) × width (ft)) × rainfall (ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
(47 ft × 27 ft) × (10.5 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.80 = net runoff (gal)
1,269 ft^2 × 0.875 ft × 7.48 gal/ft^3 × 0.80 = 6,644 gal

6,644 gal = net runoff

Based on this, a realistic estimate of the volume of water that could be collected off the 47 foot by 27 foot example roof in an average year is 6,644 gallons.

RUNOFF COEFFICIENTS

The runoff coefficient is defined as a decimal fraction of water that runs off a surface onto which it falls. A runoff coefficient of 1.00 means that 100% of the water runs off the surface; a runoff coefficient of 0.00 means all rainwater will infiltrate into the soil (none runs off; this can happen with highly mulched and vegetated landscapes); 0.50 means that half the water falling on the surface will sink in, the other half running off.

The runoff coefficients on this page are rough estimates, for they are dependent on many factors, among them:

- Climate and season of the year (which will affect whether the ground is saturate frozen, for instance; the type of precipitation, and the amount of vegetation tha be supported)
- Soil type (clayey soils allow less water to infiltrate and have higher runoff coefficients, while sandy porous soils will have low ones)
- Slope of the surface (runoff coefficient will be higher on a sloped surface versus one)
- Vegetation: amount, type, and spacing (generally, more vegetation leads to mor infiltration, and a lower runoff coefficient)
- Intensity of rainfall (a heavy or prolonged rain will produce greater runoff as th or its surface becomes saturated; a light rainfall may just cling to the soil surface vegetation and evaporate)

The following runoff coefficients are for the southwestern U.S., though they give ballpark ranges for many situations:

- Impervious paving or a building's roof: range 0.85-0.95
- Healthy Sonoran Desert Uplands: range 0.20-0.70, average 0.30-0.50
- Bare earth: range 0.20-0.75, average 0.35-0.55
- Grass/lawn: range 0.05-0.35, average 0.10-0.25
- For gravel, use the coefficient of the surface below the gravel.

For additional runoff coefficients and information see water.me.vccs.edu/courses/CIV246/table2.htm

EXAMPLE CALCULATING *ANNUAL* NET RUNOFF FROM A *BARE SECTION OF YARD*:

In an area receiving 18 inches of rain in an average year, you want to calculate the runoff from a 12 foot by 12 foot bare section of yard that drains to an adjoining infiltration basin. The soil is clayey and compacted, and you estimate its runoff coefficient to be 60% or 0.60.

catchment area (ft^2) × rainfall (ft) × 7.48 (gal/ft) × runoff coefficient = net runoff (gal)

12 ft × 12 ft × (18 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.60 = net runoff gal
144 ft^2 × 1.5 ft × 7.48 gal/ft^3 × 0.60= 969 gal

969 gal = net runoff

Based on this, a realistic estimate of the volume of runoff that could be collected off the 12 foot by 12 foot section of bare earth within the adjoining infiltration basin is 969 gallons in an average year.

EXAMPLE CALCULATING RUNOFF FROM A SINGLE STORM EVENT ON ESTABLISHED LAWN (GRASS):

The runoff coefficient for this established lawn is assumed to be 20% or 0.20, and the maximum storm event is 3 inches:

12 ft × 12ft × (3 in ÷ 12 in/ft) × 7.48 gal/ft^3 × 0.20 = net runoff gal
144 ft^2 × 0.25 ft × 7.48 gal/ft^3 × 0.20 = 54 gal

54 gal = net runoff

For another example, illustration, and more explanation see box 1.4 and fig. 1.21

Equation 5B.
Estimated Net Runoff from an Impervious Catchment Surface Minus Potential Water Loss (metric units)

catchment area (m^2) × rainfall (mm) × runoff coefficient = net runoff (liters)

EXAMPLE:

In an area receiving 304 millimeters of rain a year, you have a rooftop catchment surface that is 15 meters long and 9 meters wide, and you want to know how much rainfall can realistically be collected off that roof in an average year. You want a conservative estimate of annual net runoff, so you use a runoff coefficient of 80% or 0.80. (Since the roof is a rectangular area, use the following calculation for catchment area as in Equation 1B—CATCHMENT AREA m^2 = LENGTH m × WIDTH m—which is figured into the equation below.) Note: An explicit conversion to liters is not necessary in this equation because there are 1,000 mm/m and 1,000 liters/m^3.

(length (m) × width (m)) × rainfall (mm) × 0.80 = net runoff (liters)
(15 m × 9 m) × 304 mm × 0.80 = net runoff (liters)
135 m^2 × 304 mm × 0.80 = 32,832 liters

32,832 liters = net runoff
A realistic estimate of the volume of water that could be collected off this 15 meter by 9 meter roof in a year of average rainfall is 32,832 liters.

For another example, illustration, and more explanation see box 1.4 and fig. 1.21

Equation 6.

Circular or Oval Infiltration Basin Water-Holding Volume or Capacity, and Volume of Soil Excavated from Basin

$$\pi \times R^2 \times \text{depth} = \text{volume}$$

- π = 3.14
- **R**, **Radius** is half the diameter. **Diameter** is the distance from one side of a circ basin to the other, measured across the middle of the basin. To get an approxim average diameter of a basin with sloping or terraced banks, measure this distanc about halfway down the depth of the basin. If the basin is an oval shape, measu the short diameter and the long diameter, add them up, and divide by two to g the average diameter.
- **Depth** is the distance from the top of a basin's rim, or the top of the lip of the overflow spillway if you have one, to the bottom of the basin.

This calculation will give you a conservative estimate of the basin's water-surge capacity since it does not take into account any of the water that will rapidly

infiltrate into a well-constructed basin's soil and vegetation during the water surge.

Using this information also gives you a conservative estimate of the expanded or *swelled* volume of excavated soil you will have, since loose, excavated soil has more air incorporated into it than unexcavated soil. The average *swell factor* of excavated soil is 30% (more if clay, less if sand). This is important information if you need to estimate the volume of soil you need to transport somewhere else.

Use the same units for all measurements.

For instance, all English measurements should be in feet. The resulting English-unit basin capacity/volume will be in cubic feet, which you can convert to gallons by multiplying cubic feet by 7.48 gallons/cubic foot.

Metric measurements should be in meters. The resulting metric-unit basin capacity/volume will be in cubic meters, which you can convert to liters by multiplying cubic meters by 1000 liters/cubic meter.

EXAMPLE (ENGLISH UNITS):

To calculate the approximate gallons of water that a 1.5-foot deep oval basin with a relatively level bottom and sloping or terraced banks can hold, start by measuring the long and short oval diameters about halfway down the depth of the basin. In this example, you find that the longest diameter of the basin is 8 feet, and the shortest diameter of the basin is 5 feet.

To get the average diameter, add the two diameters together, then divide the sum by two (8 + 5 = 13, 13 ÷ 2 = 6.5 feet, average diameter). To get the average radius, divide by two again (6.5 ÷ 2 = 3.25 feet, average radius).

$3.14 \times (3.25\ \text{ft})^2 \times 1.5\ \text{ft} = 49.74\ \text{ft}^3$ capacity of the basin, and the volume of excavated soil (without the swell factor).

To convert cubic feet to gallons, multiply by 7.48 gal/ft^3

$49.74\ \text{ft}^3 \times 7.48\ \text{gal/ft}^3 = 372$ gallons

See Equation 8 to estimate the basin's average annual capacity, and Equation 9 to estimate the basin's ballpark dollar per gallon (or liter) cost.

To account for the swell factor of excavated soil, multiply the soil volume by 30% (or 0.30) then add that to the total volume:

$49.74\ \text{ft}^3 \times 0.30 = 14.9\ \text{ft}^3$.

So, $49.74\ \text{ft}^3 + 14.9\ \text{ft}^3 = 64.64\ \text{ft}^3$ of excavated soil (with the swell factor).

Trucking and landscape material companies typically measure materials in cubic yards. To convert cubic feet to cubic yards, divide the volume in cubic foot by 27 ft^3/ yd^3. So, 64.64 ft^3 ÷ 27 ft^3/ yd^3 = 2.39 yd^3 of excavated soil (with the swell factor)

For another example, illustration, and more explanation see box 2.2

Equation 7.
Square of Rectangular Infiltration Basin Water-Holding Volume or Capacity, and Volume of Soil Excavated from Basin

length × width × depth = volume

- **Length** is the longer of the two horizontal dimensions of a rectangular basin. T an approximate average length of a basin with sloped or terraced banks, measur length about halfway down the depth of the basin.
- **Width** is the shorter of the two horizontal dimensions of a rectangular basin. T an approximate average width of a basin with sloped or terraced banks, measure width about halfway down the depth of the basin.
- **Depth** is the distance from the top of a basin's rim, or the top of the lip of the overflow spillway if you have one, to the bottom of the basin.

This calculation will give you a conservative estimate of the basin's water-surge capacity since it does not take into account any of the water that will rapidly infiltrate into a well-constructed basin's soil and vegetation during the water surge.

Using this information also gives you a conservative estimate of the expanded volume of excavated soil you will have, since loose, excavated soil has more air incorporated into it than unexcavated soil. The average *swell factor* of excavated soil is 30% (more if clay, less if sand). This is important information if you need to estimate the volume of soil you need to transport somewhere else.

Use the same units for all measurements.
For instance, all English measurements should be in feet. The resulting English-unit basin capacity/volume will be in cubic feet, which you can convert to gallons by multiplying cubic feet by 7.48 gallons/cubic foot.

Metric measurements should be in meters. The resulting metric-unit basin capacity/volume will be in cubic meters, which you can convert to liters by

multiplying cubic meters by 1000 liters/cubic meter.

EXAMPLE (ENGLISH UNITS):

To calculate the approximate volume of water in gallons that a 2-foot deep rectangular basin with a relatively level bottom and sloping or terraced banks can hold, measure the length and width. In this example, you find that the length is 11 feet and the width is 7 feet, as measured about halfway down the depth of the basin.

11 ft × 7 ft × 2 ft = 154 ft^3 capacity of the basin, and the volume of excavated soil (without the swell factor)

To convert to gallons multiply by 7.48 gal/ft^3

154 ft^3 × 7.48 gal/ft^3 = 1,151 gallons

See Equation 8 to estimate the basin's average annual capacity, and Equation 9 to estimate the basin's ballpark dollar per gallon cost.

To account for the swell factor of excavated soil, multiply the soil volume by 30% (or 0.30) then add that to the total volume:

154 ft^3 × 0.30 = 46.2 ft^3. So, 154 ft^3 + 46.2 ft^3 = 200.2 ft^3 of soil excavated

Trucking and landscape material companies typically measure materials in cubic yards. To convert cubic feet to cubic yards, divide the volume in cubic foot by 27 ft^3/ yd^3. So, 200.2 ft^3 ÷ 27 ft^3/ yd^3 = 7.4 $yards^3$ of excavated soil (with the swell factor).

For another example, illustration, and more explanation see box 2.2

Equation 8. Estimate Infiltration Basin's Minimum Annual Water-Harvesting Volume or Capacity

basin capacity × number of good rainfalls/year = minimum annual water-harvesting capacity of the basin

This calculation assumes that during each good rainfall in a year's time, the basin is filled to the top with water from a combination of direct rainfall and water runon flowing into the basin from adjacent areas. This calculation provides a conservative minimum estimate of the average annual water-harvesting capacity of the basin. It is conservative because it does not take into account the water that will rapidly infiltrate into a well-constructed basin during a good rainfall, allowing even more

water runon to be harvested in that basin during the same rainfall. For purposes of this estimate, a good rainfall is assumed to be one inch of rain in English units, or 25 millimeters in metric units.

Use the same units for all measurements.

English measurements should be in gallons.

Metric measurements should be in liters.

EXAMPLE (ENGLISH UNITS):

To approximate the minimum average volume of water that a basin could capture in a year, use the example 372-gallon basin from Equation 6, and assume an average annual rainfall of 12 inches, arriving in a series of 12 good-sized rainfalls over the year. A *good-sized rainfall* in this context generates enough runoff to fill the basin. This is determined by the volume of rainfall, and the size and quality of the catchment surface directing its runoff to the basin (Equations 4B and 5B). A 1-inch (25-mm) storm is typically sufficient, but even a 0.5-inch (12.5-mm) storm may be enough depending on your catchment and the intensity of the rain.

Divide 12 inches/year of rainfall by 1-inch/rainfall = 12 good water-harvesting rainfalls/year.

372 gallons × 12 good rainfalls/year = minimum of 4,464 gallons/year of basin water-harvesting capacity

EXAMPLE (METRIC UNITS)

To approximate the minimum average volume of water that a basin could capture in a year, use an example 1500-liter basin and assume an average annual rainfall of 300 millimeters, arriving in a series of 12 good-sized rainfalls over the year. A *good-sized rainfall* in this context generates enough runoff to fill the basin. This is determined by the volume of rainfall, and the size and quality of the catchment surface directing its runoff to the basin (Equations 4B and 5B). A 25-mm rain is typically sufficient, but even a 12.5-mm rain may be enough depending on your catchment and the intensity of the rain.

Divide 300 millimeters/year of rainfall by 25-millimeters/rainfall = 12 good water-harvesting rainfalls/year.

1500 liters × 12 good rainfalls/year = minimum of 18,000 liters/year of basin water-harvesting capacity

Equation 9.
Estimate of Cost to Build Infiltration Basin per Annual Water-Holding Volume or Capacity

cost to construct basin ÷ minimum annual water-harvesting capacity of the basin = cost per volume of stored water

To estimate the construction cost per unit of a basin storage capacity over a year's time, first add up the total cost to construct the basin including labor, curb cuts, mulch, permits, dirt removal, rock to stabilize banks, and any other associated costs. Next, divide that by the minimum annual water-harvesting capacity of the basin to get the cost per unit of water-harvested capacity. The resulting cost just reflects the first year of basin use. Basins keep harvesting water for many years, so the cost per unit of stored water keeps going down every year.

Note that a basin or other earthwork infiltrating all its surface water within 12 hours or less has a much higher water-harvesting and flood-controlling capacity than an equal-sized tank, which can remain full or fullish for weeks or months after a good rain depending on how quickly and often the users open the tap and use the water.

EXAMPLE (ENGLISH UNITS):

To estimate the construction cost per unit of basin storage capacity over a year's time in English units, use the example basin from Equation 8 that has a minimum of 4,464 gallons/year of basin water-harvesting capacity, and assume a total cost to construct the basin was $800.

$800 ÷ 4,464 gallons/year = $0.18/gallon to build the basin in the first year of use —and this cost keeps going down year after year

EXAMPLE (METRIC UNITS):

To estimate the construction cost per unit of basin storage capacity over a year's time in metric units, use the example basin from Equation 8 above that has a minimum 18,000 liters/year of basin water-harvesting capacity, and assuming a total cost to construct the basin was $800.

$800 ÷ 18,000 liters/year = $0.04/liter to build the basin in the first year of use—and this cost keeps going down year after year

Equation 10A.
Berm 'n Basin (b'nb): Approximate Maximum Water-Holding Capacity or Volume (English units)

1/2 × width (ft) × depth (ft) × length (ft) = volume (ft^3)

For example, illustration, and more explanation see box 3.2

Equation 10B.
Berm 'n Basin: Approximate Maximum Water-Holding Capacity or Volume (metric units)

1/2 × width (m) × depth (m) × length (m) = volume (m^3)

Measure the width, depth, and length of the b'nb using the definitions provided in box 3.2. Remember that every cubic meter contains 1,000 liters.

0.5 × width (m) × depth (m) × length (m) × 1,000 liters/m^3 = b'nb capacity (liters)

EXAMPLE:

A b'nb is 6 meters wide, 0.5 meters deep, and 15 meters long.

0.5 × 6 m × 0.5 m × 15 m × 1,000 liters/m^3 = b'nb capacity (liters)
15 m^3 × 1,000 liters/m^3 = 22,500 liters

Equation 11A.
Berm 'n Basin: Approximate Capacity in Cubic Feet per Foot of Length (English units)

0.5 × width (ft) × depth (ft) × length (1 ft) = b'nb capacity (ft^3/1 ft length of b'nb)

For an example, illustrations, and more explanation see box 3.2

Equation 11B.
Berm 'n Basin: Approximate Capacity in Liters per Meter of Length (metric units)

0.5 × width (m) × depth (m) × length (1 m) × 1,000 liters/m^3 = b'nb capacity (liters/1 m length of b'nb)

This calculates the water-holding capacity for each 1 meter length of the b'nb instead of for a specific length.

EXAMPLE:

For the b'nb that is 6 meters wide and 0.5 meters maximum depth:

0.5 × 6 m × 0.5 m × 1 m × 1,000 = 1,500 liters/1 m length

You will need this information to calculate metric b'nb spacing distance (Equation 12B).

Equation 12A.
Berm 'n Basin Spacing Distance (English units)

(b'nb water holding capacity (ft^3/1 ft length)) ÷ (runoff coefficient × rainfall from a large storm (ft)) = b'nb spacing distance (ft)

For an example, illustrations, and more explanation see box 3.3

Equation 12B.
Berm 'n Basin Spacing Distance (metric units)

b'nb water-holding capacity (liters/1 m length) ÷ (runoff coefficient × rainfall from a large storm (mm)) = b'nb spacing distance (m)

See box 3.3 for more information. Again you will use the runoff coefficients found in Equation 5 and the result from the b'nb capacity per meter length (Equation 11B). Note: An explicit conversion to liters is not necessary in this equation because there are 1,000 mm/m and 1,000 liters/m^3.

EXAMPLE:

Using 1,500 liters per meter length (Equation 11B), and assuming a runoff coefficient of 0.30 from established grass growing in poor soil, you want to catch every drop from a maximum 50-mm storm:

(1,500 liters per 1 m length) ÷ (0.30 × 50 mm) = 100 m

So the b'nb spacing distance in this case is 100 meters or less.

Equation 13A.
Terraces: Approximate Water-Holding Capacity or Volume (English units)

width (ft) × depth (ft) × length (ft) = volume of water-holding capacity (ft^3)

For an example, illustrations, and more explanation see box 4.1

Equation 13B. Terraces: Approximate Water-Holding Capacity or Volume (metric units)

width (m) × depth (m) × length (m) × 1,000 (liters/m^3) = volume of water-holding capacity (liters)

See box 4.1 for information on width, depth, and length measurements.

Equation 14A. Terrace Capacity per Foot of Length (English units)

width (ft) × depth (ft) × length (1 ft) = terrace capacity (ft^3/1 ft length of terrace)

For an example, illustrations, and more explanation see box 4.1

Equation 14B. Terrace Capacity per Meter of Length (metric units)

width (m) × depth (m) × length (1 m) × 1,000 liters/m^3 = terrace capacity (liters/1 m length of terrace)

EXAMPLE: METRIC UNITS

This terrace is 7 meters wide, and 10 centimeters (0.10 meters) deep. Note that you need to multiply by 1,000 liters/m^3 to get a result in liters.

7 m × 0.10 m × 1 m × 1,000 liters/m^3 = 700 liters per 1 meter of terrace length

Equation 15A. Terrace Spacing Distance (English units)

Use the same equation as 12A, substituting "terrace" for b'nb

Equation 15B. Terrace Spacing Distance (metric units)

Use the same equation as 12B, substituting "terrace" for b'nb

Equation 16: Optimum Terrace Width

maximum depth of cut in the soil ÷ the degree of the slope = width of terrace

Note that "maximum depth of cut" refers to the depth of soil, which can be shallow on steep slopes.

For an example, illustrations, and more explanation see box 4.2

Equation 17. Engineering Calculation for Diversion-Swale Sizing

There are two steps needed to calculate an adequate size for the diversion swale. The *first step* is to estimate the maximum water flow into the swale. The second step is to estimate what dimensions the swale will need to have to handle this inflow.

For the first step, we will use what engineers refer to as the Rational Method to estimate peak water flow. Note that the Rational Method is best used as a simple formula for small properties, and is not considered applicable for large catchments (i.e. over 300 acres or 121 ha). For large catchments the Soil Conservation Service "Curve Number" approach is recommended, for which references are widely available.

The basic formula of the Rational Method is:

$$Q = CiA$$

where Q = peak flow (cubic feet per second)
C = runoff coefficient for the catchment
i = rainfall intensity (inches per hour)
A = catchment area (acres)

The runoff coefficient is dimensionless, theoretically varying between 0 and 1. The runoff coefficient is smaller for catchments that have high infiltration and higher for those with low infiltration. Typical runoff coefficients are: paved areas 0.9; residential lots 0.3-0.7 (dependent on amount of impervious area, type of soil and amount of vegetation); unmodified ground 0.2-0.6 (dependent on type of soil and amount of vegetation).

The rainfall intensity the swale is designed for can vary, but we suggest using a 100-year rainfall event recurrence interval. A 100-year rainfall event is defined as a rainfall of a given duration of time that can be expected to occur in the area once in a 100-year period. To estimate peak flow, rainfall duration should match the time of

concentration for the catchment. The time of concentration for the catchment is defined as the length of time after rain begins that all portions of the catchment contribute to catchment outflow. The minimum time of concentration to use is 5 minutes, which would apply to most residential properties. Larger scale applications will have larger times of concentration, which can be either estimated with personal judgment, observed directly on site during a storm, or found using the formula below.

$$T_c = 0.0078\ L^{0.77}\ S^{-0.385}$$

where T_c is time of concentration (minutes)
L is length of channel through the catchment from boundary to outflow (feet)
S is slope (ft/ft)

After the time of concentration is obtained, search on-line for NOAA's Precipitation Frequency Data Server (PFDS) to find rainfall depth. This government-data website allows you to focus on different regions of the U.S., and then pull up a table of rainfall depths for different rainfall durations (such as 5 minutes) and different recurrence intervals (such as 100 years). With the rainfall depth we can calculate rainfall intensity:

$$i\ (\text{inches per hour}) = 60 \times \text{rainfall depth (inches)} \div T_c\ (\text{minutes})$$

Catchment area in acres should be straightforward to measure. To convert square feet to acres, divide by 43,560. Now we have all variables necessary to calculate peak flow.

Peak Flow Example Calculation:
Consider a typical Tucson, Arizona, property about 0.2 acres in size.

The runoff coefficient is estimated at 0.4.

We estimate the time of concentration to be 5 minutes.

For a weather site listed in Tucson, using the map found at on-line at NOAA's Precipitation Frequency Data Server (PFDS) webpage, the rainfall depth associated with a 5-minute storm of 100-year recurrence is 0.77 inches. The rainfall intensity is 9.24 inches per hour.

The peak flow (q) associated with design conditions is 0.75 (rounded up) cubic feet per second.

After estimating the peak flow, the *second step* is to size the diversion swale to handle the peak flow. For this we will use the Manning equation to estimate average velocity of flow in a given-dimensioned swale and see if this is adequate to pass the design flow. Through iteration, minimum dimensions of the swale can be estimated. The Manning equation is:

$$V = (1.49\ R^{2/3}\ S^{1/2}) \div n$$

where V = velocity (feet per second)
R = hydraulic radius (feet)
S = slope (ft/ft), here slope is vertical fall divided by horizontal distance
n = Manning's roughness factor

Hydraulic radius is the linear distance across the most limiting (smallest) swale cross-section, measured along the earth from the swale edge down to the bottom, across the swale floor, and up to the facing swale edge. A typical Manning's roughness factor for an earth swale is 0.05. A very clean swale might be as low as 0.03, and a very obstructed (i.e. with check dams) swale might carry a roughness as high as 0.1. After velocity has been estimated with the Manning equation, the volume capacity of the swale can be found by multiplying velocity by the most limiting cross-sectional area of the swale.

SWALE VOLUME-CAPACITY CALCULATION EXAMPLE:

Continuing the example of a typical Tucson property begun above, suppose we are planning to excavate a diversion swale with hydraulic radius of 2 feet, a slope of 1/100, and a cross-sectional area of 0.3 square feet. Let's use a typical Manning's roughness value of 0.05. Velocity and volume are then:

$$V = 1.49 \times 2^{2/3} \times 0.01^{1/2} \div 0.05$$
$$= 4.73 \text{ feet per second}$$

$$Q = V \times A$$
$$= 4.73 \times 0.3$$
$$= 1.41 \text{ cubic feet per second}$$

The 1.41 surpasses the 0.75 result as found in step one using the Rational Method, so we're good to go. The designed swale would still have capacity beyond the 100-year rainfall event associated with the time of concentration for the catchment. While the swale could be sized smaller and still handle the 0.75 cubic feet per second design flow, the margin might come in handy as swales tend to fill in over time (reducing the cross-section) or as any vegetation in the swale matures (increasing the Manning's roughness factor).

REFERENCES:

David R. Maidment, ed., Handbook of Hydrology, McGraw-Hill Inc, 1992.

dipper.nws.noaa.gov/hdsc/pfds/ Accessed 6/7/0-

Equation 18.
Estimating Rock Volume and Tonnage for Ordering Materials

Your supplier may charge by the English ton (metric ton), or by the cubic yard (cubic meter) for rock— though charging by weight is generally more accurate. See below for how to calculate both. (Thanks to Steve Carson of Rangeland Hands, Inc. for these calculations.)

Note that when building an in-channel structure such as a one-rock dam, the 'width' refers to the width of the channel the structure is built in. In the example below, this width is equal to 10 feet (3 meters). The length of the structure is the distance the structure covers from upstream to downstream. In the example below, the length is 5 feet (1.5 meters). This way of referring to width and length is different than that used in traditional geometry, where width is the shorter dimension and length is the longer dimension.

EXAMPLE (ENGLISH UNITS):

Step 1: Calculate area of rock structure:

width (ft) × length (ft) = area (ft^2)

Example: A one-rock dam is 10 feet in width and 5 feet in length. To determine its volume in square feet: 10 ft × 5 ft = 50 ft^2 rock structure area

Step 2: Calculate rock structure volume based on rock size:

The standard rock size used in hand-built structures is 6- to 12-inch rock, which represents a rough range of the dimensions of the rock. A mix of 6- to 12-inch rock will have an average dimension of 9 inches [(6 in + 12 in) ÷ 2 = 9 in]. Converted to feet, this equals 0.75 feet (9 in ÷ 12 in/ft = 0.75 ft). This is the height of your one-

rock dam structure in feet. This is multiplied by area to calculate the rock structure volume.

area (ft^2) × height (ft) = volume (ft^3)

Example: The one-rock dam is 10 feet in width, 5 feet in length, and 0.75 feet in height. To determine its volume:

10 ft × 5 ft × 0.75 ft = 37.5 ft^3 rock structure volume

Step 3: Convert cubic feet to cubic yards:

Rock might be ordered by the cubic yard. A cubic yard equals 27 cubic feet. To convert cubic yards to cubic feet, divide by 27.

Example: A one-rock dam has a volume of 37.5 ft^3. To determine its volume in cubic yards:

37.5 ft^3 ÷ 27 ft^3/yd^3 = 1.38 yd^3 rock structure volume

Step 4: Convert cubic yards to tons:

Sometimes, rock is bought by the ton. A ton of rock = 1.5 × cubic yards of rock.

Example: A one-rock dam has a volume of 1.38 yd^3. To determine its weight in tons:

1.38 yd^3 × 1.5 = 2.08 tons of rock needed to build a 10-ft wide, 5-ft long, 0.75-ft high one-rock dam

EXAMPLE (METRIC UNITS):

Step 1: Calculate area of rock structure:

width (m) × length (m) = area (m^2)

Example: A one-rock dam is 3 meters in width and 1.5 meters in length; to determine its volume in square feet: 3 m × 1.5 m = 4.5 m^2 rock structure area

Step 2: Calculate rock structure volume based on rock size:

The standard rock size used in hand-built structures is 15- to 30-centimeter rock, which represents a rough range of the dimensions of the rock. A mix of 15- to 30-cm rock will have an average dimension of 22.5 centimeters [(15 cm + 30 cm) ÷ 2 = 22.5 cm]. Converted to meters, this equals 0.225 m (22.5 cm ÷ 100 = 0.225 m). This is the height of your structure in meters. This is multiplied by area to calculate the rock structure volume.

area m^2 × height (m) = volume (m^3)

Example: The one-rock dam is 3 meters in width, 1.5 meters in length, and 0.225 meters in height; to determine its volume:

3 m × 1.5 m × 0.225 m =1 m^3 rock structure volume

Step 3: Convert cubic meters to metric tons:

Sometimes, rock is bought by the metric ton. A cubic meter of rock weighs around 1600 – 1800 kilograms. To convert this to metric tons, divide kilograms by 1000 kilograms per metric ton.

weight (kg) ÷ 1000 kg/metric ton = metric tons

Example: A one-rock dam has a volume of 1 m^3. To determine its weight in tons:

1700 kg ÷ 1000 kg/metric ton = 1.7 metric tons of rock needed to build a 3 meter wide, 1.5 meters long, and 0.225 meter high one-rock dam

ON-LINE VOLUME CALCULATORS AND MORE

For a website that may have some useful calculators for you see https://www.aqua-calc.com/page/volume-calculators

Appendix 3
Sizing and Implementing a Kitchen Resource Drain (KRD) in Arizona, Code Clarification, and Recommended Changes to the Code

This appendix builds on information presented on the KRD in the Variations and Real-Life Examples sections of chapter 12. The following information is presented here rather than in chapter 12 because much of it is specific to current Arizona Department of Environmental Quality (ADEQ) regulations that are likely to change as the system is more widely used and tested. Updates on the changes will be easier to make in this appendix (and at HarvestingRainwater.com) than in the book's core.

Thanks to revisions in the code that took effect January 1, 2018,[1] the sizing and implementation of the KRD has been significantly simplified and improved since the first edition of this book and appendix were published.

The primary simplification/improvement to the code is a clarification that ADEQ does *not* require greywater harvesting systems to have a back up connection to a sewer or septic system (though a county or city code may differ) (fig. A3.1). This was not clear before ADEQ's code was revised. So in the old edition of this appendix, guidance was given to size and install the KRD to handle kitchen sink blackwater and all household greywater. That is not needed and has been removed from this revised appendix.

As stated in The Type 1 Recycled Water General Permit for Gray Water R18-9-D701-A-7 (revised January 1, 2018): "If blockage, backup, or

overload of the (*gray water*) system occurs, gray water distribution shall cease until the deficiency is corrected." Said another way, if blockage, backup, or overload of part of a greywater system occurs, stop using it, fix it, then resume use as you would with any other plumbing issue.

SIZING

This KRD-sizing discussion is based on requirements specified in ADEQ's Aquifer Protection Permit provisions R18-9-E303-F-1-i and R-18-9-E302-C-4-b found in Arizona Administrative Code Title 18 – Environmental Quality. These sizing requirements strictly apply only when ADEQ or its delegated authority is issuing a permit for a compost toilet (the KRD is currently permitted under the compost toilet permit—see the *Clarifying the Code* section of this appendix). However, these provide useful guidance for sizing any KRD—with or without a compost toilet permit. Check to see if regulations in your county or city differ from ADEQ's to determine whether KRDs can be used in your location and what your local sizing requirements are—though most areas do use ADEQ's regulations.

The size of the KRD's interceptor is determined based on the potential volume of water going down the drain. In Arizona, the size of the interceptor is calculated based on the number of bedrooms and water fixture units in the home. This approximates the number of people potentially using the system and the system's peak daily flow. The minimum interceptor capacity is 42 gallons (159 liters) for a one-bedroom house with seven or fewer fixture units (fig. A3.1). For each additional bedroom, up to a total of three, you need an additional 42 gallons (159 liters) in interceptor capacity. Note that a kitchen sink counts as two fixture units per provision A314-4-ii. For each additional bedroom over three, you need an additional 25 gallons (95 liters) in interceptor capacity.

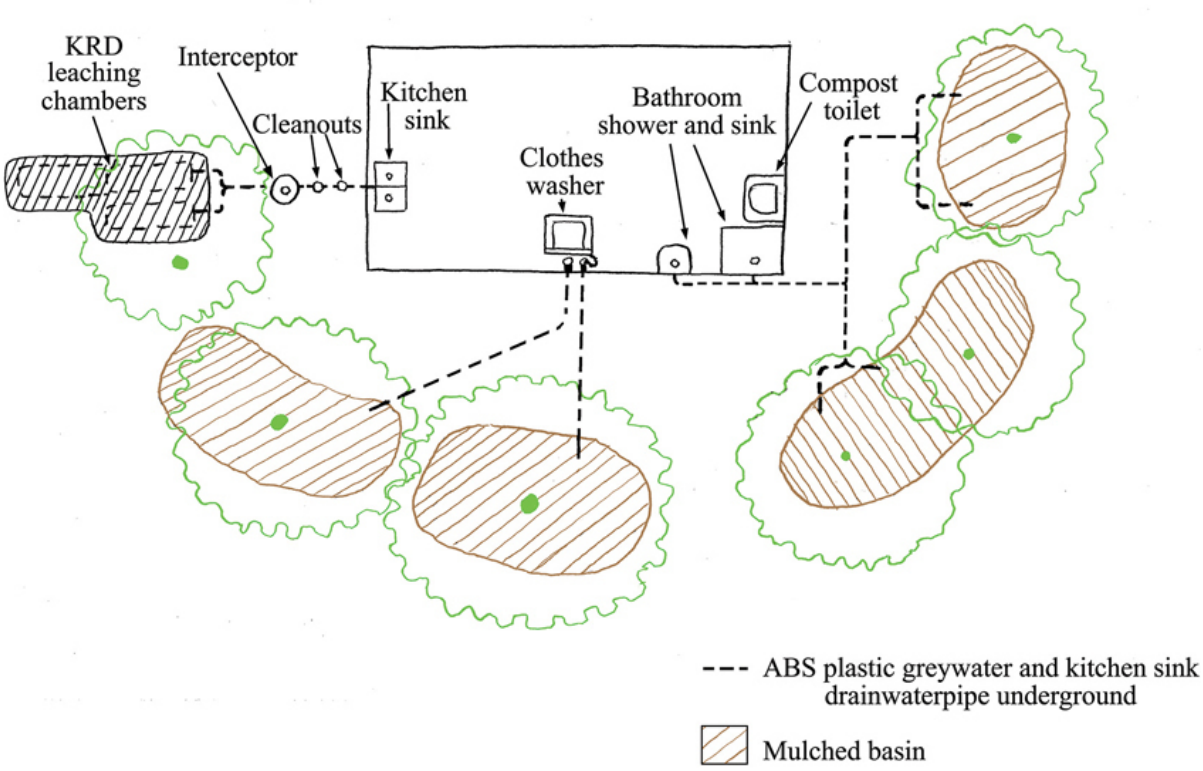


Fig. A3.1. Plan view of a Kitchen Resource Drain, compost toilet, and greywater system for a single-bedroom household having no sewer or septic system in Arizona. The number/size of the KRD's leaching chambers was determined based on the design flow (box A3.2) and the site's soil percolation rate (box 12.11). Note 1: The greywater-harvesting basins here were also sized to maximize the passive harvest of roof runoff (though that is not required). Note 2: Try to minimize distance of pipe runs to ensure you can maintain a minimum 2% slope in all pipes, while still reaching the desired outlet points in the landscape or chambers.

Note that a commercial grease trap could be used as an interceptor instead of the 50-gallon plastic drum interceptor in figs. A3.2 and 12.34, but it would be more expensive due to the size requirements. If the 50-gallon plastic drum interceptor does not meet size requirements, consider installing a second 50-gallon plastic drum interceptor in-line with the first.

Box A3.1. A Potential Conversion of the KRD Chamber's Inspection Pipe to an Auxiliary Air Vent

David Omick likes to use the KRD's leaching chamber inspection pipe as an auxiliary air vent. So instead of putting a cap atop the inspection pipe, he glues two 90° elbows together to form an upside down "U", then slides one end of the "U" over the

inspection pipe(s) of the chamber(s) farthest from the interceptor. The other end of the "U" is covered with a piece of aluminum mosquito/window screen that is hose-clamped in place to keep out vectors such as insects. Adding the two 90° elbows makes it harder for woodpeckers to peck and damage the screen. Assuming that the plumbing system is properly vented through the roof and the interceptor is properly plumbed for flow-through ventilation, the auxiliary air vent will permit a draft through the chambers and out the roof vent. This allows more air into the chamber to aid beneficial aerobic decomposition of organic matter and to improve treatment levels. This should also reduce odors and direct them out the vent stack that exits above the home's roof, rather than emitting odors from the chamber's auxiliary air vent. Securely place— but do not glue—the 90° elbows of the vent in place, so you can easily remove them to routinely inspect the interior of the chambers and to check them if you smell odors coming from the chamber vent. If there are odors, you can remove the elbows and replace them with a cap to prevent air and odors from exiting the inspection pipe.

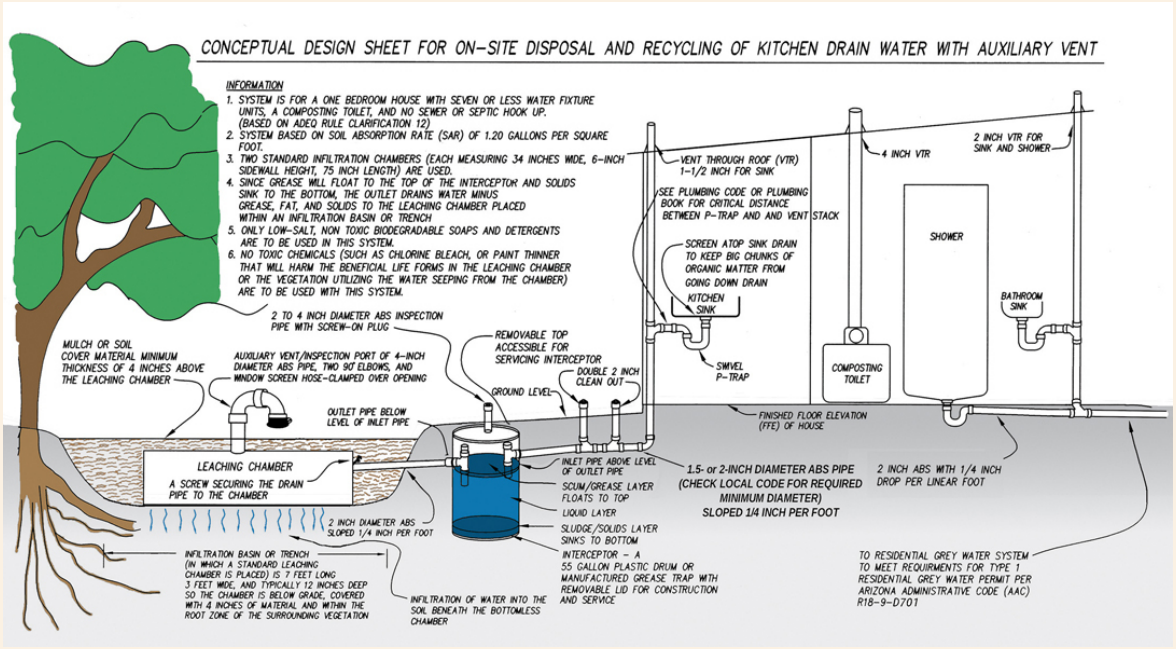

CONCEPTUAL DESIGN SHEET FOR ON-SITE DISPOSAL AND RECYCLING OF KITCHEN DRAIN WATER WITH AUXILIARY VENT
INFORMATION
1. SYSTEM IS FOR A ONE BEDROOM HOUSE WITH SEVEN OR LESS WATER FIXTURE UNITS, A COMPOSTING TOILET, AND NO SEWER OR SEPTIC HOOK UP. (BASED ON ADEQ RULE CLARIFICATION 12)
2. SYSTEM BASED ON SOIL ABSORPTION RATE (SAR) OF 1.20 GALLONS PER SQUARE FOOT.
3. TWO STANDARD INFILTRATION CHAMBERS (EACH MEASURING 34 INCHES WIDE, 6-INCH SIDEWALL HEIGHT, 75 INCH LENGTH) ARE USED.
4. SINCE GREASE WILL FLOAT TO THE TOP OF THE INTERCEPTOR AND SOLIDS SINK TO THE BOTTOM, THE OUTLET DRAINS WATER MINUS GREASE, FAT, AND SOLIDS TO THE LEACHING CHAMBER PLACED WITHIN AN INFILTRATION BASIN OR TRENCH
5. ONLY LOW-SALT, NON TOXIC BIODEGRADABLE SOAPS AND DETERGENTS ARE TO BE USED IN THIS SYSTEM.
6. NO TOXIC CHEMICALS (SUCH AS CHLORINE BLEACH, OR PAINT THINNER THAT WILL HARM THE BENEFICIAL LIFE FORMS IN THE LEACHING CHAMBER OR THE VEGETATION UTILIZING THE WATER SEEPING FROM THE CHAMBER) ARE TO BE USED WITH THIS SYSTEM.
VENT THROUGH ROOF (VTR) 1-1/2 INCH FOR SINK
4 INCH VTR
2 INCH VTR FOR SINK AND SHOWER
SEE PLUMBING CODE OR PLUMBING BOOK FOR CRITICAL DISTANCE BETWEEN P-TRAP AND AND VENT STACK
SHOWER
SCREEN ATOP SINK DRAIN TO KEEP BIG CHUNKS OF ORGANIC MATTER FROM GOING DOWN DRAIN
KITCHEN SINK
BATHROOM SINK
2 TO 4 INCH DIAMETER ABS INSPECTION PIPE WITH SCREW-ON PLUG
REMOVABLE TOP ACCESSIBLE FOR SERVICING INTERCEPTOR
MULCH OR SOIL COVER MATERIAL MINIMUM THICKNESS OF 4 INCHES ABOVE THE LEACHING CHAMBER
AUXILIARY VENT/INSPECTION PORT OF 4-INCH DIAMETER ABS PIPE, TWO 90° ELBOWS, AND WINDOW SCREEN HOSE-CLAMPED OVER OPENING
DOUBLE 2 INCH CLEAN OUT
SWIVEL P-TRAP
COMPOSTING TOILET
GROUND LEVEL
OUTLET PIPE BELOW LEVEL OF INLET PIPE
FINISHED FLOOR ELEVATION (FFE) OF HOUSE
LEACHING CHAMBER
A SCREW SECURING THE DRAIN PIPE TO THE CHAMBER
INLET PIPE ABOVE LEVEL OF OUTLET PIPE
1.5- or 2-INCH DIAMETER ABS PIPE (CHECK LOCAL CODE FOR REQUIRED MINIMUM DIAMETER) SLOPED 1/4 INCH PER FOOT
2 INCH ABS WITH 1/4 INCH DROP PER LINEAR FOOT
SCUM/GREASE LAYER FLOATS TO TOP
LIQUID LAYER
2 INCH DIAMETER ABS SLOPED 1/4 INCH PER FOOT
SLUDGE/SOLIDS LAYER SINKS TO BOTTOM
INFILTRATION BASIN OR TRENCH (IN WHICH A STANDARD LEACHING CHAMBER IS PLACED) IS 7 FEET LONG 3 FEET WIDE, AND TYPICALLY 12 INCHES DEEP SO THE CHAMBER IS BELOW GRADE, COVERED WITH 4 INCHES OF MATERIAL AND WITHIN THE ROOT ZONE OF THE SURROUNDING VEGETATION
INTERCEPTOR - A 55 GALLON PLASTIC DRUM OR MANUFACTURED GREASE TRAP WITH REMOVABLE LID FOR CONSTRUCTION AND SERVICE
INFILTRATION OF WATER INTO THE SOIL BENEATH THE BOTTOMLESS CHAMBER
TO RESIDENTIAL GREY WATER SYSTEM TO MEET REQUIRMENTS FOR TYPE 1 RESIDENTIAL GREY WATER PERMIT PER ARIZONA ADMINISTRATIVE CODE (AAC) R18-9-D701

Fig. A3.2. Kitchen Resource Drain with the inspection pipe doubling as an auxiliary vent. Compare this to an alternate installation in fig. 12.34. Credit: Drawn by Bill Cunningham P.E., Southwest-Solar.com

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Water flows out of the interceptor drain into the soil via one or more bottomless quonset-hut-style leaching chambers (figs. 12.15 to 12.18). Leaching chambers vary in size depending on the model and manufacturer. Call around to see what's available from local plumbing, septic system, or water-harvesting system suppliers. Common dimensions for one standard-style chamber with a capacity of 47 gallons (178 liters) are 34 inches (86 cm)

wide, 53 inches (135 cm) long, and 8 inches (20 cm) tall at its louvered sidewall (12 inches [30 cm] tall at peak of chamber). This chamber has an effective absorption area of 28.4 square feet (2.6 m^2).

An even better option—though sometimes harder to find—is a shorter low-profile chamber, such as Infiltrator's Quick 4 Plus Standard Low Profile chamber. With a shorter chamber you can dig a shallower trench and discharge the water from the chamber higher in the soil profile. This enables more effective bioremediation and natural filtration of the water because the density and diversity of beneficial bioremediating soil microorganisms exponentially increases the closer you get to the soil's surface (see figs. 12.4A, B). There will also be more roots higher in the soil profile to beneficially reuse the water.

The Standard Low Profile chamber's dimensions for a 32-gallon (121-liter) unit are 34 inches (86 cm) wide, 53 inches (135 cm) long, and 6.3 inches (16 cm) tall at its louvered sidewall (8 inches [20 cm] tall at the peak of the chamber). This chamber has an effective absorption area of 27.1 square feet (2.5 m^2). See box A3.2, section 5 to see how the effective absorption area of chambers is determined. Multiple chambers can be connected to one another to increase overall capacity.

Box A3.2. Steps for Determining the Number of KRD Leaching Chambers Needed for a Residence with Compost Toilet, and No Sewer or Septic Hookup, Using ADEQ Regulations

If prior to the permitting process you want to get an idea of how many leaching chambers your KRD system would require in Arizona, David Omick describes how to do it:

1) Determine the following:

   a) Number of bedrooms in residence and number of fixture units that drain to KRD
   b) Percolation test rate (in minutes per inch) of soil where leaching chambers will be placed. Note: ADEQ may require a consultant to do a soil analysis in addition to the percolation rate, depending on site characteristics.
   c) Dimensions of infiltration chambers you plan to use, including exterior width of bottom of chamber, height of louvered sidewalls, and length of chamber (go to manufacturer's website to find these dimensions)

Example:

a) 1 bedroom and 2 fixture units (kitchen sink counts as two fixture units)

b) Percolation test rate: 2 minutes per inch

c) Quick 4 Plus Standard Low-Profile chamber (from Infiltrator Water Technologies website): 34-inch width, 6.3-inch louvered sidewall height, 53-inch length

2) On line search "Arizona Administrative Code Title 18, chapter 9." As of this writing, the URL is https://apps.azsos.gov/public_services/CodeTOC.htm#ID18

3) In Arizona Administrative Code Title 18, scroll to R18-9-E303, then scroll to subsection F-1-d-i. In the first column of the table, choose the number of bedrooms and fixture units and note the corresponding design flow in gallons per day.

Example: 1 bedroom and 2 fixtures (for the kitchen sink) equals a design flow of 90 gallons per day.

Note: A 90 gallon per day design flow is unlikely in average daily use, but meant to be a conservative number in the equation to ensure the system is not undersized for a peak flow day.

4) Scroll to R18-9-A312, then scroll to D, then scroll to 2. In the first column of the table, choose the percolation rate that corresponds to the results of your percolation test. In the second column, note the corresponding SAR (soil absorption rate) in gallons per day per square foot.

Example: percolation test result is 2 minutes. SAR = 1.20 gallons per day per square foot

5) Scroll to R-18-9-E302, then scroll to subsection C, then 4, then a. Using the formula given, determine the effective absorption area of each chamber:

$A = (1.8 \times B \times L) + (2 \times V \times L)$

where

i. "A" is the effective absorption area of each chamber
ii. "B" is the exterior width of the bottom of the chamber
iii. "V" is the vertical height of the louvered sidewall of the chamber
iv. "L" is the length of the chamber

If prior to the permitting process you want to get an idea of how many leaching chambers your KRD system would require in Arizona, David Omick describes how to do it:

1) Determine the following:

a) Number of bedrooms in residence and number of fixture units that drain to KRD

b) Percolation test rate (in minutes per inch) of soil where leaching chambers will be placed. Note: ADEQ may require a consultant to do a soil analysis in addition to the percolation rate, depending on site characteristics.

c) Dimensions of infiltration chambers you plan to use, including exterior width of bottom of chamber, height of louvered sidewalls, and length of chamber (go to manufacturer's website to find these dimensions)

Example:

a) 1 bedroom and 2 fixture units (kitchen sink counts as two fixture units)

b) Percolation test rate: 2 minutes per inch

c) Quick 4 Plus Standard Low-Profile chamber (from Infiltrator Water Technologies website): 34-inch width, 6.3-inch louvered sidewall height, 53-inch length

2) On line search "Arizona Administrative Code Title 18, chapter 9." As of this writing, the URL is https://apps.azsos.gov/public_services/CodeTOC.htm#ID18

3) In Arizona Administrative Code Title 18, scroll to R18-9-E303, then scroll to subsection F-1-d-i. In the first column of the table, choose the number of bedrooms and fixture units and note the corresponding design flow in gallons per day.

In Arizona, you determine the total required volume and/or length of KRD leaching chambers based on the design flow of water entering the system and an on-site percolation test or soil evaluation (box 12.11). See box A3.2 for how to determine how many leaching chambers your site needs.

Locate KRD leaching chambers where their water output can be beneficially and conveniently reused in the landscape. The required property-line setbacks for these systems are just one-fourth of the required setbacks for conventional septic leach field chambers (excluding set-backs from domestic wells, which remain at 100 feet [30 m]). KRD chambers can be placed as close as 1.25 feet (0.37 m) to a property line, while septic leach field chambers must be at least 5 feet (1.5 m) from a property line.

Install the leaching chambers on the level bottom of an infiltration basin or trench that has been dug on contour where the soil percolation tests were conducted. This level bottom should be free of rocks and debris that could reduce the rate of infiltration of the drainwater. The basin or trench must be deep enough so the top of the chamber can be fully covered with 4 inches (10 cm) of cover material. The basin or trench should not be deeper than necessary—it's important to keep the bottom of the chamber and infiltrating water well within the root zone of surrounding plants (the top 2 feet or 0.6 m of soil) and bioremediating soil life (figs 12.4A, B). *In order to stay within the root zone and maximum soil life, I do not use chambers taller than 13 inches (33*

cm). The chambers come in a number of different sizes and heights, so be careful when you select yours. With the appropriate chamber in place, install end plates to keep it from filling with soil. A capped inspection pipe is installed through the top of the chamber and extends above grade.

After the end plates and all plumbing lines are in place, fully cover the sides and top of chambers with 4 inches (10 cm) of an appropriate material. The cover material is not specified by code, and could be soil, pumice, mulch, or finished compost.

I advise using finished compost as the cover material. Compost is rich in beneficial microorganisms that will help filter drainwater and convert organic matter, soap scum, and grease into plant nutrients. Compost will help prevent these substances from sealing the soil and will enhance percolation though the chamber's louvered sides in poorly draining clay soils. Add finished compost or mulch cover as needed over time to keep the chamber adequately covered as compost or mulch settles.

Do not fill the chamber with compost, mulch, or any other materials. The chamber cavity is intentionally left empty so roots cannot grow into it. This also leaves plenty of room for water surging through the chamber before it infiltrates into the compost and soil outside the chamber. Perennial vegetation is planted beside—not on top of—the chamber to utilize and help filter the water.

To further enhance the performance of the KRD, greywater expert David Omick makes the following recommendations:[2]

- Be careful about what you put down the drain. Avoid anything that is toxic such as lye or other chemical drain clog removers, poisons, or bleach. Use appropriate soaps (see box 12.5) and keep grease output to a minimum.
- Place a wire screen within the drain of your kitchen sink to prevent big chunks of organic matter from going down your drain (fig. 12.33). Empty the screen into a compost bucket as needed. These screens are available at most hardware and grocery stores in the kitchenware section.
- Do not install or use a garbage disposal in conjunction with this system since this could overload the KRD. It is much simpler and more efficient to

compost and reuse this organic matter in your garden or landscape. See appendix 4, for resources on composting.

You may want to consider trying a controlled experiment of a KRD with and without interceptors to see if performance changes. Greywater expert Art Ludwig suggests that an interceptor, or other grease trap device, would improve performance for households with lots of grease going down the drain, but would be a disadvantage for those with minimal grease. Simply adding more infiltration area, rather than an interceptor, might be a lower-maintenance alternative in that low-grease context.[3]

See "Reuse Via Composting Toilets and Greywater Harvesting Versus Disposal Via Septic Tanks and Sewers" in the Real-Life Examples section of chapter 12 for more information, and the "Greywater Harvesting" page of my website, HarvestingRainwater.com, for updates on KRD requirements and potential reference designs.

MAINTENANCE

On average, the interceptor will need to be pumped/emptied/cleaned about once every four years (based on a 50-gallon interceptor size and a household of two to four people). An easy way to remember to do this is to have this done around the time of every presidential election. A septic pumping service can do this for you for about $100, though the price will be more if they have to drive a long distance to get to you.

CLARIFYING THE CODE

In Arizona, you can get a permit for a home that has a compost toilet, greywater reuse in the landscape, and a KRD that reuses kitchen sink drainwater, with no sewer or septic hook up. But I want to clarify a section of potentially confusing wording in the code (revised January 1, 2018) to ensure you get the correct permit and build the most simple and effective system, rather than a needlessly complex one.

In section 3.a. of R-18-9-E303. 4.03. (the General Permit for Composting Toilet, Less Than 3000 Gallons Per Day Design Flow, which also permits the KRD) the code states, "A permittee may use a composting toilet only if:

wastewater is managed as provided in this Section and, if gray water is separated and reused, the gray water reuse complies with 18 A.A.C. 9, Article 7" (section R18-9-D-701).

OK, that part is clear enough. The KRD will manage the kitchen sink blackwater, but when you go to the greywater requirements R18-9-D701—Type 1 Recycled Water General Permit for Gray Water—subsection R18-9-D701-A-11 states:

> *"For a residence using an on-site wastewater treatment facility for black water treatment and disposal, the use of a gray water system does not change the design, capacity, or reserve area requirements for the on-site wastewater treatment facility at the residence, and* ***ensures the facility can handle the combined black water and gray water flow****;"*

This is where there could be some confusion. In this context, one might mistakenly interpret "facility" to mean the KRD, and thus think the KRD system must be designed and built to handle the combined black water and greywater flow. That is incorrect.[4] In this context, the correct interpretation of "facility" is the whole on-site wastewater system, which is made of three parts—the compost toilet, the greywater system, and the KRD. The KRD only handles the kitchen sink blackwater. The greywater system only handles the greywater. And the compost toilet ensures there is no blackwater produced by the toilet. So the KRD system only needs to be designed and built to handle the kitchen sink black water.[5]

R-18-9-E303. 4.03. section E ensures the compost toilet is adequately sized; section F ensures the KRD (or similar system) is adequately designed to handle kitchen sink blackwater flows, and section A.3.a. ensures the greywater system is sized to handle the greywater flows. It was not intended in either the greywater or the compost toilet regulations for the KRD system to be designed to handle blackwater flows that might come from a toilet.[6]

In a different context, where a house is connected to a septic tank—given the way the septic tank section of the code is currently written—the septic tank system must be sized to handle all household waste-water (blackwater and greywater flow), which will all be blackwater once the blackwater and greywater mix within the septic tank. Furthermore, a septic tank system is a wastewater disposal system (containing more dangerous toilet blackwater),

while a greywater-harvesting system and/or a KRD system is a wastewater recycling system (devoid of any toilet blackwater), reusing that water for gravity-fed irrigation systems.[7]

And this gets us to…

THINGS THAT NEED TO BE CHANGED IN THE CURRENT CODE AS IT APPLIES TO THE KRD

As of this writing, the current code allows the use of a KRD at a residence having a compost toilet, but this scope is not comprehensive. To better serve the community, the code should be changed to allow the use of a KRD at a residence with or *without* a compost toilet.

In 2004-2005, citizen stakeholders (including me), led by David Omick and Pearl Mast, participated in an ADEQ-facilitated process to update the code. We advocated that the KRD be made a legal option for homes like David and Pearl's that do not have a sewer connection or septic system, but which rely on a compost toilet. At the time, we didn't realize such a KRD system would also be desired by people *with* sewer connections or septic systems who didn't have compost toilets, so this possibility was not considered during these rule deliberations.

But many people in Arizona with a sewer or septic hook up are harvesting their kitchen sink blackwater with neither guidance nor permits—thus illegally.[8] This is similar to what happened when thousands of people were harvesting household greywater without guidance or permits prior to the 2001 rule change that legalized greywater systems in Arizona. These 2001 regulations provided thirteen common sense guidelines or best management practices for the legal use of greywater (see the Real-Life Story—How Safe, Effective, and Accessible Residential Greywater Harvesting Was Legalized and Incentivized in Arizona at the end of chapter 12).

Here's how Chuck Graf—who helped write ADEQ's greywater rules and who is now retired—recommends changing the rule to allow KRD use by households who have a sewage collection system, septic tank, or alternative system, rather than a compost toilet:

"KRD systems should be regulated as a Type 2 general permit in its Recycled Water rules. Under the Type 2 permit, a person would notify ADEQ of their intent to install such a system and include some salient details or plans for the system as required by the rule. But that would be all. Once ADEQ is notified, the person could install the system and begin using it.

This new Type 2 permit would fit into ADEQ's four-permit hierarchy for general permits under its Aquifer Protection Permit program (which regulates many large and small discharges, including discharges from septic tanks and alternative onsite systems) and Recycled Water program (which regulates reclaimed water and greywater). In these programs, ADEQ has established Type 1, Type 2, Type 3, and Type 4 permits as follows:

Type 4 permits are used to regulate septic tanks, compost toilets, and alternative onsite systems under the Aquifer Protection Permit program. The Type 4 permit requires submittal of an application to ADEQ, issuance of a Construction Authorization by ADEQ upon satisfactory review of plans, then issuance of a Discharge Authorization upon satisfactory construction (i.e., this is the actual approval to use the system). Typically, there is an inspection of the construction by ADEQ or its designated authority before issuance of the Discharge Authorization. ADEQ also regulates sewage collection system construction/extensions with Type 4 permits. The Type 4 permits are found in AAC R18-9-E301 through E323 of the rules.

Type 3 permits require submittal of an application and plans to ADEQ. Upon satisfactory review of the plans, ADEQ issues a Discharge Authorization. Normally, there would not be an inspection. ADEQ uses these permits to ensure that proper pollution controls are implemented for activities that do not pose as great a threat to groundwater quality. These permits are found at AAC R18-9-D201 through D307.

Type 2 permits merely require notification to ADEQ that the applicant intends to undertake a particular type of activity that, because of the volume and pollutant characteristics of the discharge, poses a less significant threat to groundwater quality. Typically, this permit requires submittal of relevant information about the discharge, which may include plans and other information. ADEQ is thus able to compile a list of all such entities engaging in this type of low-impact discharge. These permits are found at AAC R18-9-C301 through C306.

Type 1 permits pertain to very low impact discharges. Under this permit, the discharger is in compliance as long as whatever criteria specified in rule are followed. There is no requirement for notification, registration, or application, and there is no fee for this permit. The household gray water permit established in ADEQ's recycled water rules is a Type 1 permit. This permit is found at AAC R18-9-D701.

Regulating KRD systems as a Type 2 permit under ADEQ's recycled water rules would take a rule change to add this new permit to the Type 2 permits that

already exist in rule. ADEQ hasn't indicated when it will open up the recycled water rules for further revisions, but it wouldn't hurt the community of KRD users to get the ball rolling to assist ADEQ in developing this permit when this does happen. KRD users, through their collective experience, could play a critical role [helping develop] the criteria for the effective and safe use of KRD systems. These criteria would include details about the design, construction, and operation and maintenance for such systems, and probably would address how manufactured products would be assessed and qualified for use by homeowners."

Mr. Graf believes that utilization of the Type 2 permitting approach under ADEQ's recycled water rules would be far more effective for the agency, the end user, and environmental protection than trying to regulate these systems under the much more complicated Type 3 or Type 4 approach.[9]

Appendix 4
Resources

To save paper and provide the most up-to-date information and revisions, appendix 4— Resources now appears in its entirety only at HarvestingRainwater.com. The resources provided here are distillations of some of those resources.

Soil-Carbon Sponge (Introduction)
"Regenerate Earth" by Walter Jehne. GlobalCoolingEarth.org.

Understanding Soil Health and Watershed Function, by Didi Pershouse, SoilCarbonCoalition.org.

Water Harvesting in India (Introduction)
Ripples of the Society: People's Movements in Watershed Development in India, by G. Sheena. Gandhi Peace Foundation and Food and Agriculture Organization of United Nations (FAO/UN), 1998.

Making Water Everybody's Business: Practice and Policy of Water Harvesting, edited by Anil Agarwal, Sunita Narain, and Indira Khurana. Centre for Science and Environment, 2001.

The Radiant Raindrops of Rajasthan, by Anupam Mishra, translated by Maya Jani. Research Foundation for Science, Technology and Ecology, 2001.

Dying Wisdom: Rise, Fall, and Potential of India's Traditional Water Harvesting Systems, edited by Anil Agarwal and Sunita Narain. Centre for Science and Environment, 1997.

Assessing Your Site, Choosing Your Earthworks, and Tips to Achieve Greater Success (chapter 1)

Rainwater Harvesting for Drylands and Beyond, Volume 1, 3rd ed.—in color, by Brad Lancaster. Rainsource Press, 2019.

Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments, by Theib Oweis, Dieter Prinz, and Ahmed Hachum. ICARDA, 2001.

Permaculture: A Designer's Manual, by Bill Mollison, illustrated by Andrew Jeeves, manuscript and editing, Reny Mia Slay. Tagari Publications, 1988.

Every Last Drop: Rainwater Harvesting and Sustainable Technologies in Rural China, by Zhu Qiang, Li Yuanhong and John Gould. Practical Action Publishing, 2012.

Water Harvesting: Guidelines to Good Practice, by Rima Mekdaschi Studer and Hanspeter Liniger. Centre for Development and Environment, 2013.

Infiltration Basins (chapter 2)

Rain Gardens: Managing Water Sustainably in the Garden and Designed Landscape, by Nigel Dunnett and Andy Clayden. Timber Press, 2007.

Berms n' Basins (chapter 3)

The Negev: The Challenge of a Desert, 2nd ed., by Michael Evenari, Leslie Shanan, and Naphtali Tadmor. Harvard University Press, 1982.

The Collection of Rainfall and Runoff in Rural Areas, by Arnold Pacey and Adrian Cullis. Practical Action Publishing (formerly Intermediate Technology Publications), 1986.

Training Course on Water Harvesting for Improved Agricultural Production. Food and Agricultural Organization of the United Nations, CD-ROM, 2003.

Wind & Snow Harvesting (chapters 3 and 9)

HarvestingRainwater.com/wind-snow-harvesting

Terraces (chapter 4)

The Art and Craft of Stonescaping: Setting and Stacking Stone, by David Reed. Lark Books, 2000.

Infiltration Trenches (chapter 5)
Gardening with Less Water, by David A. Bainbridge. Storey Publishing, 2016.

Imprinting (chapter 6)
A Guide for Desert and Dryland Restoration: New Hope for Arid Lands, by David A. Bainbridge. Island Press, 2007.

Holistic Management, 3rd Edition: A Commonsense Revolution to Restore Our Environment, by Allan Savory and Jody Butterfield. Island Press, 2016.

Mulching (chapter 7)
Teaming with Microbes: The Organic Gardener's Guide to the Soil Food Web, Revised Edition, by Jeff Lowenfels and Wayne Lewis. Timber Press, 2010.

Food from Dryland Gardens, by David Cleveland and Daniela Soleri. Center for People, Food and Environment, 1991. CD-ROM, 2002.

Reducing Hardscape, Harvesting Its Runoff, and Creating Permeable Paving (chapter 8)
Porous Pavements, by Bruce K. Ferguson. CRC Press, 2005.

Green Infrastructure for Southwestern Neighborhoods, by Watershed Management Group. Free pdf in English or Spanish. WatershedMG.org.

Diversion Swales (chapter 9)
Handbook for Forest and Ranch Roads: A Guide for Planning, Designing, Constructing, Reconstructing, Maintaining, and Closing Wildland Roads, by William Weaver and Danny Hagans. Mendocino County Resource Conservation District, 1994.

Water Harvesting from Low-Standard Rural Roads, by Bill Zeedyk. Quivira Coalition, 2006.

Regrarians eHandbook (especially Geography and Water chapters), by Darren J. Doherty, Andrew Jeeves, and Georgi Pavlov. Regrarians Ltd, Regrarians.org.

Water for Every Farm: Yeomans' Keyline Plan, by Ken Yeomans and P.A. Yeomans. Keyline Designs, 1993.

The City Forest: The Keyline Plan for the Human Environment Revolution, by P.A. Yeomans. Keyline Publishing, 1971.

Restoring Streams in Cities: A Guide for Planners, Policymakers, and Citizens, by Ann L. Riley. Island Press, 1998.

Designing Sustainable Communities: Learning from Village Homes, by Judy Corbett and Michael Corbett. Island Press, 2000.

In-Channel Strategies (chapter 10)

Let the Water Do the Work: Induced Meandering, an Evolving Method for Restoring Incised Channels, by Bill Zeedyk and Van Clothier. Chelsea Green Publishing, 2014.

Erosion Control Field Guide, by Craig Sponholtz and Avery C. Anderson. Quivira Coalition and Watershed Artisans, 2012.

Groundwork: A Handbook for Small-Scale Erosion Control in Coastal California, 2nd edition, by Liza Prunuske, Chris Choo, Mike Jensen, and Harold Appleton of Prunuske Chatham, Inc., Marin Resource Conservation District and Marin County Stormwater Pollution Prevention Program, 2007.

Vegetation (chapter 11)

Bringing Nature Home: How You Can Sustain Wildlife with Native Plants, by Douglas W. Tallamy. Timber Press, 2009.

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Understanding Roots, by Robert Kourik. Metamorphic Press, 2015.

Mycorrhizal Planet: How Symbiotic Fungi Work with Roots to Support Plant Health and Build Soil Fertility, by Michael Phillips. Chelsea Green Publishing, 2017.

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Edible Forest Gardens, Volumes 1 and 2, by Dave Jacke and Eric Toensmeier. Chelsea Green Publishing, 2013.

https://www.harvestingrainwater.com/plant-lists-resources/multi-use-rain-garden-plant-lists/

NeighborhoodForesters.org

Greywater Harvesting (chapter 12)
The New Create an Oasis with Greywater 6th Edition: Integrated Design for Water Conservation, Reuse, Rainwater Harvesting, and Sustainable Landscaping, by Art Ludwig. Oasis Design, 2015.

Oasis Builder's Greywater Guide: Installation of Greywater Systems in New Construction and Remodeling, by Art Ludwig. Oasis Design, 2015.

The Water-Wise Home: How to Conserve, Capture, and Reuse Water in Your Home and Landscape, by Laura Allen. Storey Publishing, 2015.

Composting Toilets (chapter 12)
The Humanure Handbook: A Guide to Composting Human Manure, Third Edition, by Joseph Jenkins. Jenkins Publishing, 2005.

"Living Outside the Box, a Few Simple Technologies for Daily Living," Omick.net.

Watershed Awareness and Restoration (Epilogue)
Basins of Relations: A Citizen's Guide to Protecting and Restoring Our Watersheds, 3rd edition, by Brock Dolman and Kate Lundquist. WATER Institute, Occidental Arts and Ecology Center, 2018.

Regenerative Development: A Framework for Design Beyond Resilience, by Ben Haggard and Pamela Mang. John Wiley & Sons, 2016.

Kitchen Resource Drain (appendix 3)

"Watson Wicks, an Extremely Simple and Low Cost Alternative Septic System," http://oasisdesign.net/compostingtoilets/watsonwick.htm

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Glossary

Aerobic. A condition that supports organisms that thrive only in the presence of oxygen

Air-conditioning condensate. Atmospheric water that condenses on the cold coil of an air-conditioning unit

Airshed. The total area of the atmosphere that contributes air and the potential contaminants within it to a particular site

Algae. Microscopic plants that contain chlorophyll and live in water. Algae can impart tastes and odors to stored water.

Alluvial fan. A fan-shaped accumulation of sediment forming at the base of a rill, arroyo, ravine, or canyon where the slope changes to a flatter plain

Anaerobic. A condition that supports organisms that thrive only in the absence of oxygen

Angle of repose. The maximum angle or steepness of slope at which a pile of unconsolidated material can remain stable

Angular aggregate. Aggregate whose particles are angular in shape so their flat faces interlock with each other to resist rotating and shifting. See also Open-graded aggregate.

Annual. Plant that takes one year or less to go through its entire life cycle: germination of the seed, vegetative growth, flowering, and seed production, after which it dies

Apron. A platform of rocks acting as a stabilizing check-dam spillway that absorbs and breaks up the erosive force of water spilling over the dam

Aquifer. Subterranean layers of sedimentary particles (sand, gravel, and rocks) laid down over geologic time, in which water fills the tiny spaces between the particles

Arroyo. A water-carved gully or channel in arid lands, usually somewhat small with steep banks, and dry most of the time due to infrequent rainfall and the shallowness of the cut, which does not penetrate below the level of permanent ground water

Auxin. A natural plant hormone that regulates various functions of plant growth, including cell elongation

Bankfull. A flow of water through a watercourse that just fills the channel to the top of its banks and at a point where the water begins to overflow onto a floodplain

Batter. A deliberately constructed lean of a retaining wall back toward the slope to prevent shifting soil from eventually toppling the wall

Berm 'n basin. A water-harvesting earthwork laid perpendicular to land slope, consisting of an excavated basin and a raised berm located just downslope of the basin

Biocide. A poisonous substance, such as a pesticide or herbicide

Biocompatible. A material whose decomposition creates products that are beneficial for, or at least not harmful to, the environment in which it is deposited

Biofiltrate. The science of filtering water-borne pollutants with plants and other living organisms

Bioremediate. The use of living organisms such as bacteria, fungi, and vegetation to clean up or remove other pollutants from soil, water, and wastewater

Blackwater. Wastewater from toilets (some regulators consider kitchen sink and dishwasher wastewater as blackwater too), that has higher levels of solids and coliform bacteria than greywater sources

Bladed land/Blading. Practice of scraping away topsoil and compacting remaining subsoil with large earth-moving machinery to create a building pad devoid of organic matter

Bleed-off (cooler). Water discharged from evaporative coolers to remove accumulating salts

Boomerang berm. Semicircular berm open to, and harvesting, incoming runoff from upslope

Branched drain greywater system. System of pipes, valves, or "double L" or "Y" fittings that "branch" or split a gravity-fed flow of greywater to as many as sixteen outlets within mulched basins distributed in a landscape

Break line. The dividing "line" in a landscape where a slope changes from a gentle grade where sediments settle out of slow-moving runoff, to steep grades where sediments are picked up and carried away by faster-moving runoff

Brownfields. Abandoned or underused industrial or commercial facilities where redevelopment is complicated by environmental contamination of soils and/or water

Btu. British Thermal Unit. A unit used to measure the energy required to raise the temperature of 1 pound of water by 1 degree Fahrenheit. One Btu equals 252 calories, 778 foot-pounds, or 0.293 watt hours.

Buildout. A vegetated water-harvesting basin or other strategy used to narrow a road and slow traffic

Canale. Roof drain found on Santa Fe-style buildings with parapet walls

Carbon cycle. The series of natural processes by which carbon compounds are beneficially captured, converted, and released in the environment, such as capturing carbon dioxide into living tissue of plants via photosynthesis, converting that carbon into vegetation and other soil-based life, and the potential release of some or all of that carbon through natural respiration and the decay of dead organisms

Catchment surface. Surface from which runoff is captured with earthworks or a cistern for beneficial on-site use

Central Arizona Project (CAP). A multibillion dollar canal project that diverts water from the Colorado River and pumps it 1,000 feet (300 meters) uphill and over 300 miles (482 km) through the desert to reach farms and the cities of Phoenix and Tucson, Arizona

Channel flow. The concentrated distribution of runoff within distinct channels or drainages. Look for nick points, rills, gullies, bank cutting, different sediment sizes, vegetation growing within channels, and exposed roots to assess the force of the flow and the health of the channel.

Channelization. Constricting and straightening water flow by sealing and smoothing the banks and sometimes the bed of a waterway, often with concrete. It can be compared to a shotgun barrel for water. Channelization increases the velocity of water flow through, and downstream of, the channelized area, reducing infiltration of water into the soil and sometimes deepening the channel.

Check dam. A low, leaky barrier placed perpendicular to the flow of water within a drainage to slow the water's flow, infiltrate more water into the soil, and hold soil and organic matter higher in the watershed

Chill hours. The number of winter hours below 45˚ F needed for dormant deciduous trees grown in warm-winter climates to leaf out and flower in the spring. The number of winter hours above 60˚F is subtracted from the number of hours below 45˚ F to figure the number of hours of chill received for a particular day.

Cistern. A tank used to store rainwater

Coliform bacteria. Common bacteria, found in soil and water, that grow in the intestines of warm-blooded animals. Generally they are not harmful, and testing water for total coliforms is not a suitable indicator of fecal contamination. Instead, test for Escherichia coli (E. coli) when measuring microbial quality of drinking water and the presence of fecal contamination.

Combined sewer. Sewer that contains sewage, household waste-water, and rain runoff from streets, yards, and driveways

Commodify. To turn a natural resource into a limited-access commodity to be bought, sold, and hoarded

Commons. A natural resource or ecosystem that provides the ecological basis of life and whose sustainability and equitable allocation depends on cooperation among its community members

Communify. To work together to enhance a natural resource and the related community by managing the sustainable, fair use, and equal accessibility of the resource

Community. Represents all living and interacting organisms in an ecosystem, including people, other animals, plants, fungi, and bacteria

Compost. A soil amendment made from decomposed organic matter. The act of composting speeds up the decomposition of the organic matter, while retaining more nutrients by keeping the compost pile moist (in a pit, in the shade, covered in mulch), lightly aerated, and by balancing the amount of carbon material (dry woody material like straw or sawdust) to nitrogen-rich material (green plant material, fresh manure, urine), which also prevents odors.

Composting toilet. A waterless toilet in which dry carbon-rich material such as straw or sawdust is added to its aerobic composting chamber to help decompose (without objectionable odor) nitrogen-rich human feces and urine into high-grade fertilizer

Contour berm. A berm 'n basin constructed along a contour line

Contour line. A level line perpendicular to the slope of the land

Coppice/coppicing. A method of cutting/pruning trees and shrubs to obtain wood without killing the plant, while also encouraging new vigorous growth

Crossover riffles. Also called a "meander crossover," this is a straight section of drainage where sediments naturally deposit in areas of slower-moving water.

Culvert. A drainage pipe made to transport water beneath a roadway. Metal culverts can be made into above-ground cisterns.

Curb cut. An opening in a street-side curb that allows street runoff to exit the road and enter and infiltrate well-mulched and vegetated street-side water harvesting earthworks

Daylighting pipe. Outletting a pipe into the open air

Daylighting a waterway. Uncovering and revegetating a previously piped or buried waterway to recreate a natural, living watercourse.

Deciduous. A characteristic of a plant to seasonally drop its leaves to better survive cold, heat, or drought

Debris. Large items that could clog a rainwater system, such as a downspout screen, irrigation emitter, or permeable pavement. Debris may include leaves, branches, sediment, or trash.

Degenerative. A type of investment that starts to degrade or break down as soon as it is made, requires on-going investments of energy and outside inputs to keep it functional, *consumes* more resources than it produces, and typically serves only *one* function

Detention/Retention basin. A structure that decreases stormwater flow from a site by temporarily or permanently holding the runoff on site. This is not a water-harvesting structure unless the held water is beneficially utilized on site (irrigating vegetation for example).

Ditch Witch. Gas-powered ditch digger, for digging large ditches. See www.ditchwitch.com for photos and dealers.

Diversion swale. A gently sloping drainageway that moves water slowly downslope across a landscape, while simultaneously allowing some of it to infiltrate into the soil

Drip irrigation. An irrigation strategy applying water via an emitter to the root zone of a plant at a rate slow enough (usually less than 3 gallons [about 11 liters] per hour) to allow the soil to absorb it without inducing runoff

Dry farm. Farming without supplemental irrigation, and relying solely on rainfall for needed irrigation

Dryland. Area of the world where potential average yearly moisture loss (evapotranspiration) exceeds average yearly moisture gain (precipitation)

Dry-stacked retaining wall. A naturally porous wall of stone, brick, or salvaged concrete laid "dry" without mortar, and maintaining a batter or lean of 5° to 15° into the slope to help counter the weight of upslope earth

Dumpster. An exterior trash container from which opportunistic scavengers can salvage discarded resources

Ephemeral water flow. Water that flows for less than 30 consecutive days, typically seasonally or during and just after storms

Erosion. Wearing away of soil and rock by gravity, wind, and water, intensified by human land-clearing practices

Evaporation. The change of water from a liquid to a gas

Evapotranspiration. The combined measurement of water loss to evaporation and transpiration through the pores of vegetation

Evaporative cooler. Also known as swamp coolers, these coolers wet porous pads of cardboard, wood shavings, or burlap through which air passes and is then cooled by the evaporating moisture. A fan blows the cooled air into a building or area needing to be cooled.

Exotic vegetation. Plants that were originally not native to an area. In drylands, such plants often have higher water requirements than low-water-use native or indigenous vegetation, and sometimes can become invasive, but are introduced for ornamentation, fast growth, food production, or other characteristics. Examples of exotic vegetation in Tucson, Arizona, would be Chilean mesquite trees (invasive), buffle grass (extremely invasive), and citrus trees. See also Native vegetation.

Ferrocement. A method of building or a building material using cement, sand, and water to cover a reinforcing skeleton of metal wire or mesh material; often called thin shell

Filter dam. A large and sturdy one-rock dam with progressively smaller, filter-like, backfill ranging from large rocks to smaller rocks to smaller cobble to smaller gravel as you move upstream in the structure

First flush system. A device or length of capped pipe that diverts the dirtiest or foulest first flush of water running off a catchment surface away from a cistern

Flow splitter. A "double L" or "Y" pipe fitting that splits or "branches" greywater flow in two for wider passive distribution within a landscape

Foodshed. The total food system (gardeners, farmers, bakers, butchers, transportation system, markets, restaurants, etc.) and the geographical area in which it resides or travels before it gets to a particular community or mouth

French drain. A trench or basin filled with porous materials such as gravel or mulch that have ample air spaces between them allowing water to infiltrate quickly into the drain and percolate into the root zone of the surrounding soil, while creating a stable walkable surface

Gabion. A check dam in which rocks are encased in a wrapping of wire fencing or a wire basket that holds everything together, sort of a "rock burrito in a wire tortilla"

Gabion basket. A rectangular wire basket made to contain many rocks, forming a check dam across a drainage

Generative. A type of investment that starts to degrade as soon as it is made, requires on-going investments of energy and outside inputs to keep it functional, *produces* more resources than it consumes, and typically serves *multiple* functions

Geocell. A matrix of open, plastic cells that can be filled with aggregate, soil, or turf to create a stabilized porous pavement

Greywater. Wastewater originating from a clothes washer, bathtub, shower, or sink that can be safely reused to irrigate a landscape

Greywater harvesting. The practice of safely directing the grey-water generated at a site to the root zone of perennial plants in the yard where it can help grow beautiful and productive landscapes

Greywater stub out. A greywater plumbing connection installed during a building's construction or remodeling, allowing easy and inexpensive future access to the drainwater stream. To utilize the greywater, a simple greywater distribution system is set up within the landscape, then hooked up to the stub-out.

Groundwater. Water that has naturally infiltrated into and is stored within an underground aquifer

Guild. A harmonious assembly of living species such as plants, animals, and people and nonliving elements such as rocks or buildings that perform better through their cooperative interrelationships than they would as individuals

Gully. A large erosive drainage or arroyo

Hard water. A characteristic of water containing dissolved calcium and magnesium, which is responsible for most scale formation in water heaters and pipes

Hardscape. Hard paving material such as concrete sidewalks, asphalt streets, and brick patios; and buildings

Headcut. The growing upstream edge of an erosive gully or rill

Heat-island effect. A rise in temperature caused by hardscape (concrete, asphalt, buildings) that is heated by the sun, stores the heat like a battery, and then releases the heat during the evening

Heel-to-toe. Stable placement of check dams where the toe of the level terrace of accumulating soil and sediment behind a downstream dam extends to the heel of the downstream-facing base of the next upstream dam

Humanure. Composted human feces and urine used as a high-quality fertilizer

Hydrologic cycle. The continual movement of water between the earth and the atmosphere through precipitation, infiltration into and release from living systems, evaporation, evapotranspiration, and precipitation again

Impervious. A nonpermeable solid surface

Imprinter roller. An imprinting tool fabricated from a 10- to 20- foot (300–600 cm) long, 20- or 24-inch (50–60 cm)-diameter smooth roller with 10-inch (25-cm) lengths of 6 × 6-inch (15-cm) to 8 × 8-inch (20-cm) angle iron welded onto the roller in a pattern of staggered star rings. When rolled behind a tractor, each angle iron tooth will create a depressed microwatershed about 1 foot (30 cm) square, capable of holding 0.79 to 1.3 gallons (3 to 5 liters) of water per imprint on level ground. Imprinted soil will retain and encourage the infiltration of all the water from a 2- to 3.5-inch (50- to 88-mm) rainfall.

Imprinting. A water-harvesting technique used to accelerate the revegetation of disturbed or denuded land with annual precipitation from 3 to 14 inches (76 mm to 356 mm) by creating numerous small, well-formed depressions in the soil that collect seed, rainwater, sediment, and plant litter, and provide sheltered microclimates for germinating seed and establishing seedlings

Infiltration. The movement of water from the land's surface into the soil

Infiltration basin. A landscaped, level-bottomed, relatively shallow depression dug into the earth that collects, infiltrates, and utilizes the rain that falls within it, the runoff draining into it from the surrounding area, and potentially household greywater too

Infiltration chamber. An empty, bottomless, subsurface plastic chamber into which greywater is released, reducing direct human or animal contact with the greywater, and reducing the risk of roots growing into the greywater pipe

Integrated design. An efficient design methodology based on natural systems that provides on-site needs (e.g., water, shelter, food, aesthetics) with existing (but otherwise unseen/untapped) on-site resources/elements/potential (e.g., stormwater runoff, greywater, cooling shade, warming sun, vegetation) by identifying and enhancing beneficial relationships between all on-site elements in a way that helps divert, deflect, or convert the site's challenges (such as flooding and erosion) into still more resources/opportunities (like free irrigation to grow vegetative flood-and erosion-control strategies) so that a site can produce or recycle more (e.g., energy, water, money, soil fertility) than it consumes.

Intermittent water flow. Flow lasting more than 30 days, but not a full year

Jandy valve. My preferred, fully adjustable, three-way diversion valve for a household greywater distribution system

Keyline. A contour line surveyed to run through the keypoint of first, uppermost, or primary valleys on a slope. The key-point is the point where the slope of a valley starts to flatten as you walk down the slope of a watercourse. Thus, the steeper erosional slope is above the keyline and the more gradual depositional slope is below it. See also Break line.

Keyline pattern cultivation. A concept developed by farmer P.A. Yeomans that improves contour plowing through observing normal landform and topography. Successive natural contour lines vary from one another, rather than forming even parallel lines. Thus when plowing a number of furrows parallel to a contour line the plow furrows soon deviate from a true contour. Yeomans appreciated the significance of this phenomenon, and created keyline cultivation to utilize a conscious designed "off contour" drift in cultivating furrows to control the movement of rainwater for the benefit of the land. Keyline furrows direct water from wetter valleys to drier ridges to spread the water out rather than concentrating it, and to markedly increase the time of contact between rainwater and soil to increase infiltration and reduce erosion (see figs. 9.26 - 9.28).

Land subsidence. The settling or sinking of land resulting from the compaction of the sedimentary layers of an aquifer. This occurs when groundwater is withdrawn from the pore spaces of these sedimentary layers faster than the water can be naturally replaced

Landscape fabric. Permeable fabric sometimes used under gravel paving to keep gravel from migrating into the subsoil, or around French drains with perforated pipes to slow root growth into the pipe. The fabric allows water to pass through but hinders the movement of solid material. Landscape fabric is available from garden, landscape, and hardware suppliers.

Lawn roller. A cylinder that can be filled with water, then pulled with a handle and rolled over soil, gravel, or a lawn to compact and flatten the surface

Living sponge. A natural mix of fertile soil, soil organisms, organic surface mulch, and vegetation that quickly infiltrates water into the soil and pumps some of it back out through the vegetation to

produce additional resources such as food, shelter, wildlife habitat, and beauty

Low-water-use vegetation. Vegetation that, once established, can subsist on natural rainfall alone

Microcatchment. A small, localized catchment surface, such as a roof, section of road or pathway, or earthen surface directing its runoff to an adjoining water-harvesting strategy in which plants are watered directly by the harvested runoff

Microclimate. A more temperate or extreme localized climate created by the shelter or exposure of adjacent landscape features or buildings

Microorganisms. Plants or animals of microscopic size

Mulch. A porous layer of organic matter or rock on the surface of the soil that reduces soil moisture loss to evaporation, and in the case of organic matter, increases the porosity, fertility, and life of the underlying soil.

Municipal water use. Use of "city water" that you pay for, and which often is piped and pumped long distances. The source is typically surface water (such as from reservoirs or rivers) or groundwater pumped from aquifers.

Native vegetation. Vegetation indigenous to a 25-mile (40-km) radius of a site and found within 500 feet (150 m) of the site's elevation. Some sites may require defining native with a larger radius to bring in more plant diversity, but the smaller the radius the more likely that plants can thrive within the climatic constraints of the site.

Natural recharge. The rate at which water naturally fills or replenishes an aquifer

Net-and-pan system. A modified series of boomerang berms connected directly to one another, concentrating harvested runoff at multiple points in the landscape. A completed system looks like a "net" of berms draped over a hillside with "pans" or basins inside each segment of the "net."

Nitrogen-fixing. The ability of a microorganism to "fix" or convert atmospheric nitrogen gas to a chemically combined form, ammonia, which is essential to plant growth. These microorganisms have a symbiotic relationship with certain plants, whereby they live in their root nodules and convert atmospheric nitrogen into a form usable for the plant. Bacteria of the genus Rhizobium inoculate plants in the families of Leguminosae and Ulmaceae, while an actinomycete of the genus Frankia inoculates plants in the Betuleceae, Casuarinaceae, Coriariaceae, Elaeagnaceae, Myricaceae, Rhamnaceae, and Rosaceae families.

Nonpoint-source pollution. Pollutants from many diffuse sources. Nonpoint-source pollution is caused by storm-water or snowmelt moving over the ground. The runoff picks up and carries away natural and human-made pollutants, finally depositing them into lakes, rivers, wetlands, coastal waters, and even underground sources of drinking water.

Nonpotable water. Water that is not safe for human consumption without adequate filtration and/or treatment

Oasis zone (drier). An unpaved area naturally receiving more water than rainfall due to runoff from adjoining areas, but *not* receiving supplemental greywater. In the built environment the drier oasis zone is typically within 10 to 20 feet (3 to 6 m) of an impervious hardscaped area where the hardscape's runoff supports a greater density and/or diversity of vegetation.

Oasis zone (wetter). An unpaved area naturally receiving more water than rainfall due to runoff from adjoining areas *and* supplemental greywater. In the built environment the wetter oasis zone is typically around gathering spots of human caretakers like patios, front porches, and paths within 30 feet (9 m) of a home where water resources such as roof runoff and/or path and patio runoff and household greywater are readily available to support a greater density and/or diversity of vegetation.

One-rock dam (ORD). A low one-rock high, speed-hump-like, gradually-sloping grade control structure placed perpendicular to the flow of water within a water channel to slow and spread—but not stop—the flow of water and sediment. It extends five or more tightly packed rock-courses along the channel length.

On-site water budget. The total water "income" on a site is the rain falling on it, plus water gained by natural runon, minus water lost to runoff. To achieve water sustainability at a site, the annual on-site water "withdrawl" or consumption (domestic/interior and landscape/exterior) must be less than this water income. Note that greywater generated and reused on site is sometimes also included in the site's water income, but unlike rainwater, this is not necessarily a sustainable water source if originally pumped or trucked in from off site before the water is used and becomes greywater.

Open-graded aggregate. Aggregate having a narrow range of particle sizes and open void spaces that improve porosity between the particles. See also Angular aggregate.

Open-pollinated. Nonhybrid plants produced by transferring pollen from two parents from the same variety, which in turn produce offspring just like the parent plants. Heirloom vegetables are open-pollinated varieties passed down from generation to generation.

Organic. Non-genetically modified life grown or raised without synthetic fertilizers, pesticides, or sewage sludge in such a way that the fertility of associated soil improves with time

Organic groundcover. Natural materials, such as dead plant material, manure, or compost, that break down and improve the soil

Orientation. How a building or plantings are oriented in relationship to the winter's noonday sun, and the angles of the rising and setting sun year round. Buildings with their longer wall and windows facing the winter noonday sun, and shorter walls and fewer windows facing the rising and setting sun, are much easier to passively heat and cool than buildings of the opposite orientation.

Outlet chamber. An empty, bottomless, louver-sided subsurface chamber into which greywater is released, reducing the potential that people or animals come into direct contact with the greywater, and reducing the risk of roots growing into the greywater pipe

Overflow. The planned and stabilized exit route for excess water from a water-harvesting earthwork or tank

Overflow water. Excess water exceeding the storage capacity of a water-harvesting earthwork or tank

P-trap. Drain pipe in the shape of the letter "P" used to prevent sewer gas from entering a building by keeping a water seal in the bend of the pipe

Partnership. A model of relating that emphasizes equality between all people and the natural environment and its life forms. Since the primary organizational concern is not ranking, relationships do not revolve around figuring out who is boss, who is in control, or who is the steward. Rather, the primary organizational principle is linking and understanding, bringing people and whole ecosystems together in mutually beneficial relationships, and figuring out how individual responsibilities and contributions blend with natural processes to produce extraordinary creative results benefiting the whole.

Parts per million (ppm) and **parts per billion** (ppb). Used to quantify amounts of pollutants in water, and other substances

Pathogen. An organism that may cause disease

Peak surge. The highest short-term volume of expected water flow

Percolation. The downward movement of water infiltrating the soil

Perennial. Plant that lives longer than two years

Perennial water flow. Water that continually flows year round, year after year

Permaculture. A methodology of integrated, sustainable design based on natural systems

Permeable paving. A broad term for water-harvesting techniques that use porous hardscape/paving materials that let water pass through the pavement and infiltrate into soil, passively irrigating adjoining plantings, dissipating the heat of the sun, reducing soil compaction, allowing tree roots beneath the paving to breathe, filtering pollutants, and decreasing the need for expensive drainage infrastructure

pH. The measure of acidity or alkalinity ranging from 1 to 14. Below 7 is increasingly acid, 7 is neutral, and above 7 is increasingly alkaline.

Pond. An open earthen holding area for water. Ponds can be appropriate in drylands if filled with runoff harvested on site to provide a backup water supply in the dry season, but are inappropriate if groundwater or off-site water is consumed or pumped into the pond to keep it full.

Potable water. Water that is safe for human consumption and can be used for the greatest variety of uses

Rain sensor. A water-saving device that monitors rainfall and is connected to an automatic irrigation timer in order to shut the timer and irrigation off during or immediately after rainfall

Ramada. An outdoor shade structure under which it is comfortable to gather

Reclaimed water. Greywater and blackwater drained offsite, treated offsite to meet nonpotable standards, and then pumped to selected destinations for reuse

Regenerative. A type of investment that starts to grow or improve once it is made, does not require on-going investments of energy and outside inputs to keep it functional, *produces* more resources than it consumes, typically serves *multiple* functions, and can *reproduce itself*

Renewable. A resource that can be replaced in a short period of time. Renewable does not necessarily mean sustainable. For instance, the transport of "renewable" Colorado River water pumped to Tucson and Phoenix, Arizona, consumes huge amounts of resources, while over-allocation of the river has so depleted its flow that vast tracts of the Colorado River delta and much of the culture of the indigenous people of the area have been destroyed.

Reservoir. A structure for storing water. It may be open or covered.

Retaining wall. A structure that holds back a slope, preventing erosion

Reverse osmosis. A process of forcing water through porous membranes to filter out such solids as microorganisms, and organic and inorganic chemicals, to produce very pure water

Rill. A tiny erosive drainage in which loose soil has washed away. It is very common on eroding slopes where roadways have been cut into hillsides or on bare dirt driveways and roads that run downslope.

Riparian. Relating to or living within or beside a perennial body or flow of water such as a lake, spring, creek, or river

Runoff. Water that flows off a surface when more rain falls than the surface can absorb

Runoff coefficient. A number between zero and one that indicates the average percentage of rainwater that runs off a type of surface. For example, a rooftop with a runoff coefficient of 0.95 indicates that 95% of the rain falling on that roof will run off.

Runon. Runoff water that runs onto a site

Saturated soil. Soil in which the pore space is completely filled with water

Sediment. Soil, sand, and minerals washed from land into water or lower reaches of land, usually after rain. Excessive sediment can destroy fish-hatching areas; clog animal habitats, French drains, and porous pavement; and obscure waters so that sunlight does not reach aquatic plants.

Sewer. A pipe used to transport sewage elsewhere

Sheet flow. The relatively even distribution of runoff water over the land surface, following the slope of the land downward but not focused into distinct channels. Sheet flow has most likely occurred after a

large rainfall if you don't see distinct channels in an area of sloping bare dirt.

Slope. A measurable steepness indicating a change in elevation from one point to another. Slope can be measured in degrees from horizontal, percentages, and proportions. The greater the slope the greater the need for vegetation, and the more care needs to be taken in designing earthworks.

Soakin. Water that infiltrates the soil rather than being lost to runoff

Soft water. Water containing little or no dissolved calcium and magnesium

Solar access. Maintaining full winter-sun exposure to winter-sun-facing windows, solar water heaters, solar photovoltaic panels, solar ovens, and winter gardens

Solar arc. A number of shading elements such as trees, cisterns, trellises, covered porches, and overhangs laid out in the shape of an arc or semicircle, open to the winter sun and deflecting the rising and setting summer sun from any objects, such as a home or garden placed within the arc

Spillway. A planned and stabilized route for overflow water

Sponge. A material able to quickly absorb and hold water. See also Living sponge.

Spreader drain. A diversion swale variation, designed with the upper and middle portion of its basin sloping gradually, while the bottom length of the basin is constructed dead level on contour without a downslope berm, to create a very wide overflow spillway. Due to the very wide, level spillway the overflow water flows as a sheet flow.

Stabilizing. Methods used to reduce further erosion. Can include reduction of slopes, retaining walls, rock-clad spillways and aprons, and vegetation

Stewardship. The duties and obligations of a steward. The careful and responsible management of communities, natural resources, and ecosystems. The weak link of the stewardship model is that it can become a domination, rather than a partnership model. In such a case, the steward may view him- or herself as being above or dominant over that which is being stewarded, rather than being just another integral part among the myriad others, that together make up and are responsible for the health of the whole.

Stormwater. Rainwater once it has landed on a surface

Stub outs (greywater). Plumbing connections installed in new construction that allow easy future access to the drainwater stream to redirect greywater to the landscape

Subsoil. The naturally compacted soil found beneath less compacted, more organic-matter-rich topsoil

Subwatershed. A smaller watershed within, and making up part of, a larger watershed

Sun trap. An area having a more comfortable and moderate microclimate due to the site's being open to the winter's rising and noonday sun, while shaded from the afternoon sun primarily in summer

Supplemental water. An auxiliary source of water meant to augment natural on-site rainfall resources

Surface water. Water that flows on the surface of the land, such as water flowing in creeks and rivers

Surge basin. A pond placed at the inlet point of a diversion swale to diffuse the kinetic force of the incoming water with the water standing in the pond. It is often 12 to 18 inches (30 to 45 cm) deep.

Sustainable. Describes a condition or practice in which biodiversity and renewability of ecosystems, cultures, and natural resource production and quality are maintained over time

Swell factor. Excavated soil expands or swells on average by 30% due to the loose, excavated soil having more air incorporated into it than unexcavated soil

Tamping. Compacting dirt or gravel by foot stomping or other means

Terrace. A relatively flat "shelf" of soil, sometimes called a bench, built parallel to the contour of a slope. The terrace reduces the steepness of a section of a slope, reducing runoff and erosion, while increasing

infiltration. Terraces can be built with or without a retaining wall depending on the steepness of the slope.

Thermophilic. Characterized by having an inclination for high temperatures above 105˚ F (40.5˚ C), or for being able to generate high temperatures

Three-way diverter valve. A valve used to direct or divert water flow in one of two directions. Found at pool and spa supply stores, these valves can be incorporated into greywater plumbing to allow the user to send the greywater to the landscape or sewer as they please.

Tinaja. A desert water hole naturally carved into bedrock

Topsoil. The upper layer of soil containing most of the organic matter and fertility

Total dissolved solids (TDS). Indicates how many minerals and other solids are contained in one gallon or liter of water. Technically, these are the dry residues that remain after the water has been heated to 180° C.

Toxic. Any substance able to cause injury to living organisms when eaten, absorbed through the skin, or inhaled into the lungs

Transpiration. The loss of moisture from plants to the air via the stomata within their leaves

Uplands. Drier areas of a landscape having more drought-tolerant and sparse vegetation than potentially wetter lands below

Vegetation. Plants. However, in a water-harvesting context, vegetation is one form of life that emerges from a water-harvesting system, the "living cistern" that make your system regenerative. Vegetation invites rainfall and runoff water into the soil; we can then use that water in the form of shade and passive cooling, shelter, fruit, vegetables, fiber, soil-building, forage for livestock and wildlife, erosion control, building materials, herbal medicine, and beauty.

Wastewater. Water used by humans and thenconsidered a "waste" that needs to be disposed of then considered. Devaluing any water is the real waste.

Water budget (of a site). See On-site water budget.

Water softener. A device that replaces calcium and magnesium ions from hard water with sodium ions. Without the calcium and magnesium the water becomes "soft," but the added sodium or salt is not good for plants or soil. Softened water is not good for use with greywater systems, and the softener backwash is even worse since it has an even higher salt content.

Water table. The upper limit of a body of groundwater

Watercourse. An ephemeral or perennial waterway, large or small. Sometimes referred to as a drainageway, arroyo, stream, or wadi

Watershed. The total area of a landscape draining or contributing water to a particular site or drainage

Well. A human-made hole in the earth from which groundwater is withdrawn

Winter-sun side. In the northern hemisphere, the south-facing side of buildings, walls, and trees; the north-facing side is the "winter-shade side." This is because the winter sun stays in the southern sky all day. In the southern hemisphere the "winter-sun side" is the north-facing side.

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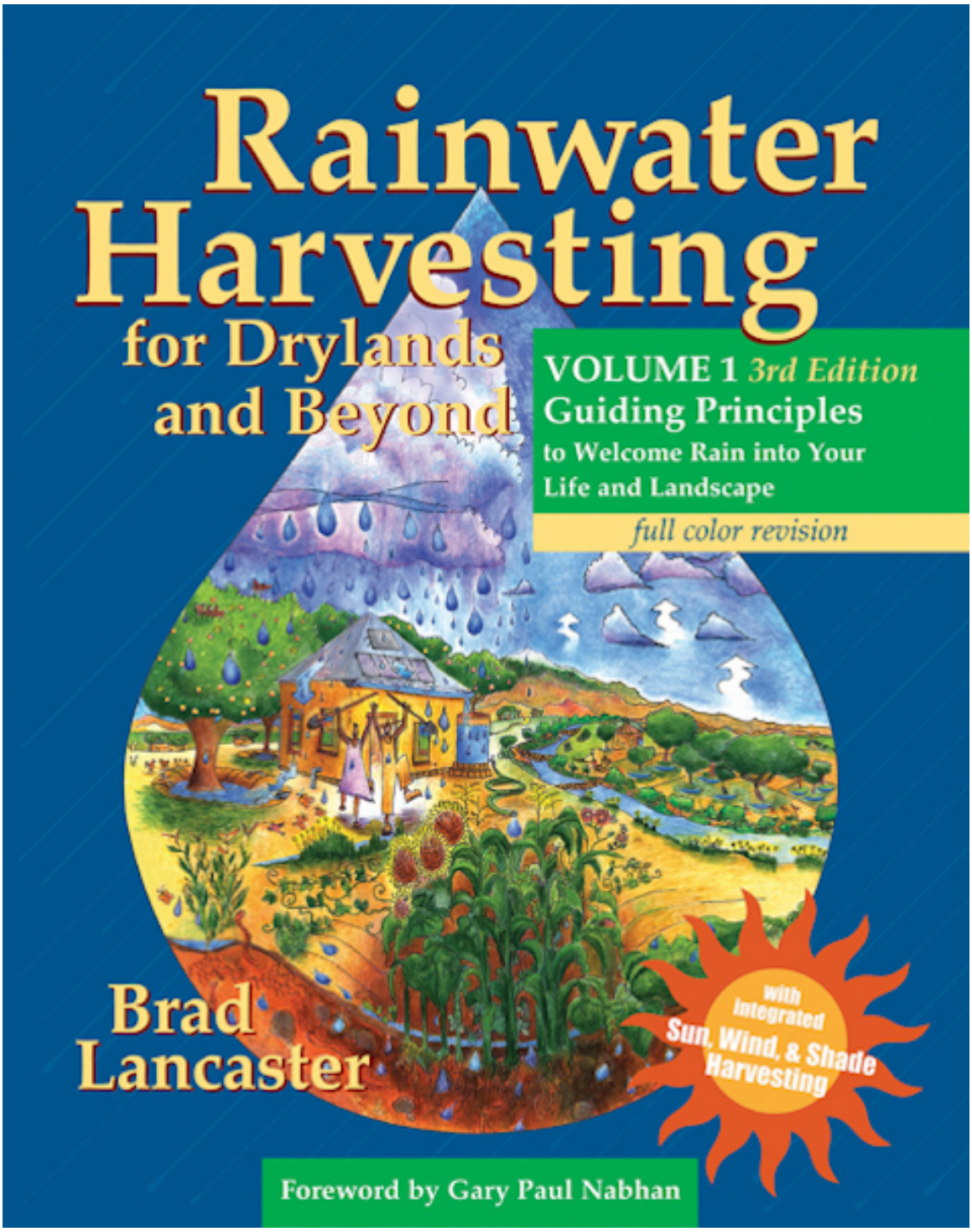
Rainwater Harvesting for Drylands and Beyond, Volume 1, *3rd Edition* – in color

Guiding Principles to Welcome Rain into Your Life and Landscape


Rainwater Harvesting
for Drylands and Beyond
VOLUME 1 3rd Edition
Guiding Principles
to Welcome Rain into Your Life and Landscape
full color revision
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with integrated Sun, Wind, & Shade Harvesting
Foreword by Gary Paul Nabhan

Turn water scarcity into water abundance! Volume 1 is the best-selling, award-winning book on how to conceptualize, design, and implement life-enhancing water-, sun-, wind-, and shade-harvesting systems for your home, landscape, and community. This book enables you to assess your on-site resources, gives you a diverse array of strategies to maximize their potential, and empowers you with

guiding principles to create an integrated, multi-functional plan specific to your site and needs.

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- How suburban homeowners and rural homesteaders in the U.S. are providing 9 100% of their water needs with the rain
- How the orientation of your home and landscape to the sun can freely heat the winter and cool them in summer, while dramatically reducing water and power needs
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- Simple calculations and figures to determine your site's rainwater and greywater budgets and water needs.
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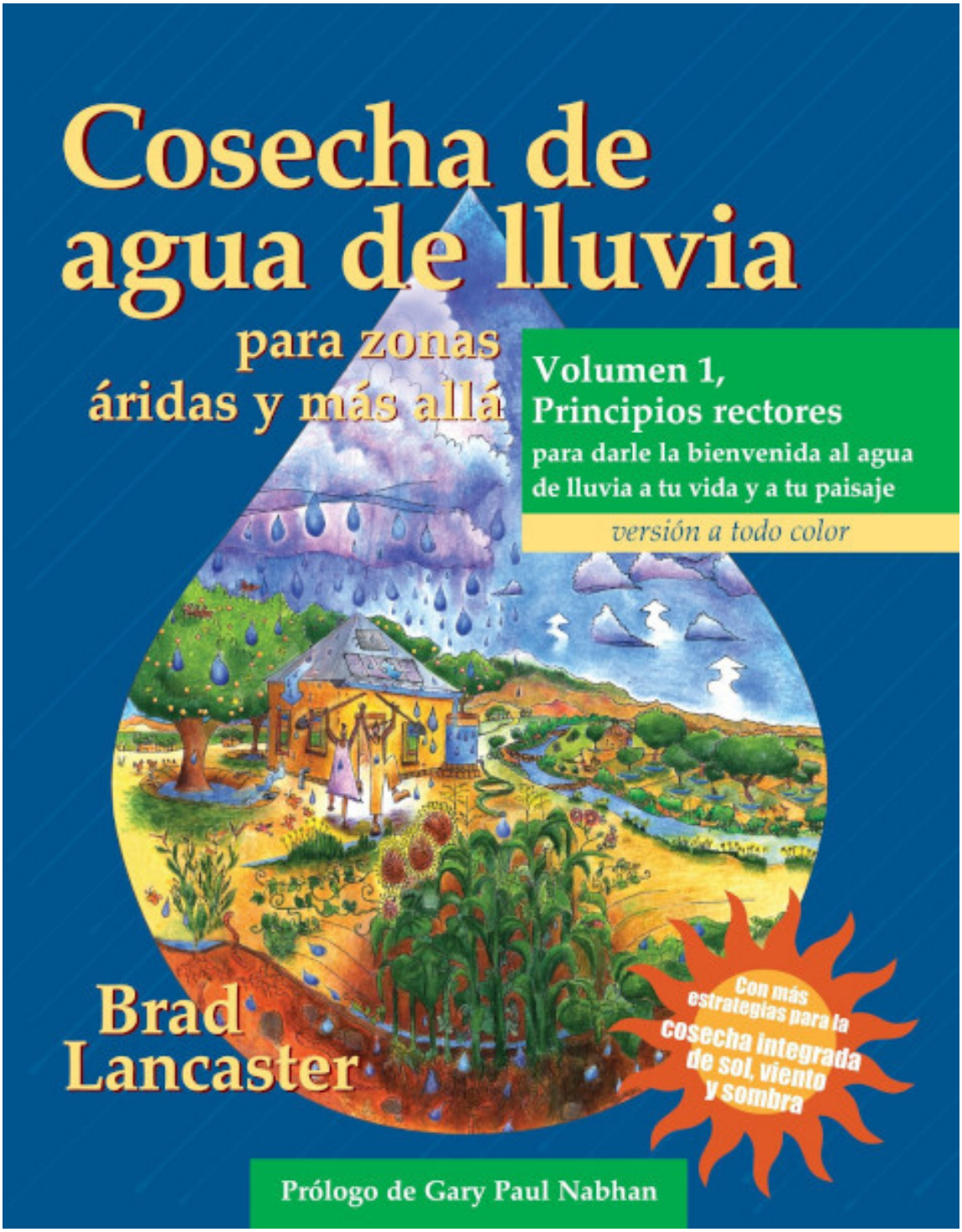
Cosecha de agua lluvia para zonas áridas y más allá

Volumen 1, Principios rectores para darle la bienvenida al agua de lluvia a tu vida y a tu

paisaje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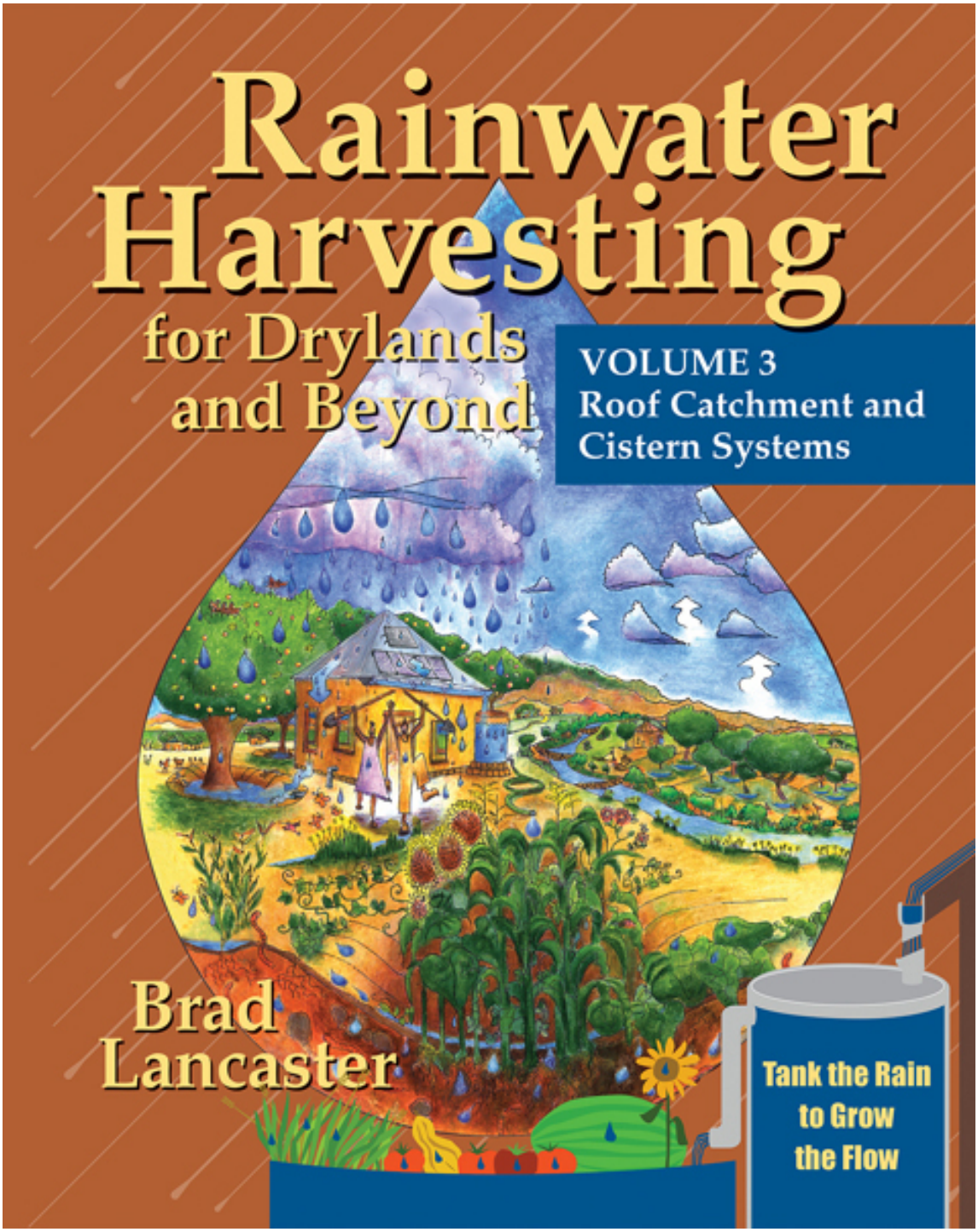
Rainwater Harvesting for Drylands and Beyond, Volume 3

Roof Catchment and Cistern Systems

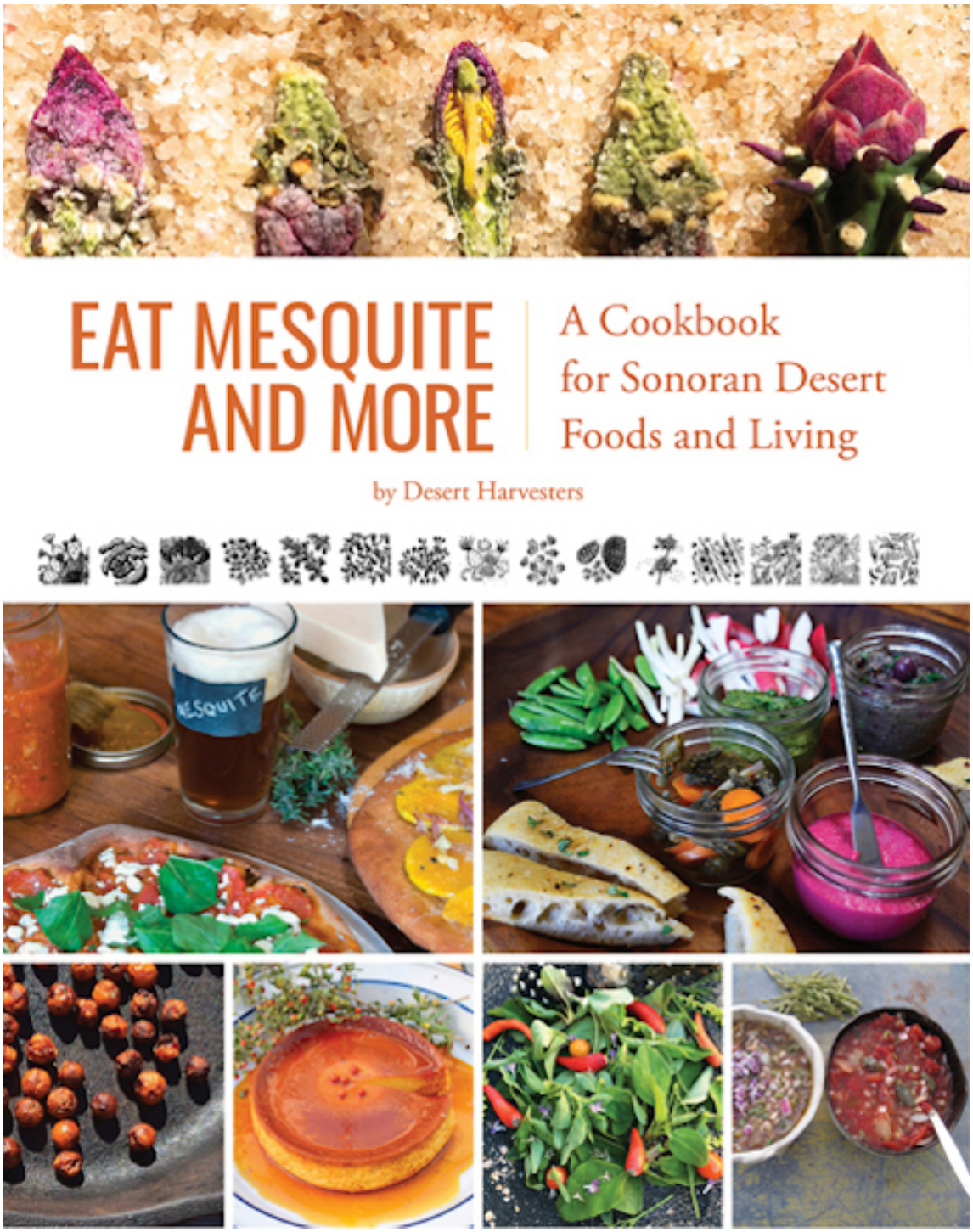


Cisterns harvesting runoff from rooftop catchments have the potential to harvest the highest quality rainwater runoff on site, and allow for the greatest range of potential uses for that water. Water uses range from irrigation to fire protection, bathing, washing, maintaining natural creek and spring flow in dry times and potable water for drinking.

Building on the information presented in Volume 1, this book shows you how to select, size, design, build, or buy and install cistern systems harvesting roof runoff. Guiding principles unique to such systems are presented along with numerous tank options, and design strategies that will improve water quality, save you money, reduce maintenance, and expand the ways you can use your tanks and the water harvested within.

Eat Mesquite and More

A Cookbook for Sonoran Desert Foods and Living



Celebrates native food forests of the Sonoran Desert and beyond with over 170 recipes featuring wild, indigenous foods, including mesquite, acorn, barrel cactus, chiltepin, cholla, desert chia, desert herbs, and flowers, desert ironwood, hackberry, palo verde, prickly pear, saguaro, wolfberry, and wild greens. The recipes—contributed by desert dwellers, harvesters, chefs, and innovators—capture a spirit of

adventure and reverence inviting both newcomers and seasoned experts to try new foods and experiment with new flavors.

More than a cookbook, this guide also encourages a renaissance of "wild agriculture," one that foregrounds the ethical harvesting and selection of wild foods and the re-planting of native food sources in urban and residential areas without imported water or fertilizers. It contains stories of significant individuals, organizations, and businesses that have contributed knowledge, products, and innovation in the planting, harvesting, and use of wild, native desert foods. Additional essays reveal the poetry of the foraging life, how to plant the rain, and medicinal uses and ethnobotanical histories of desert plants.

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